A REVIEW OF ICE INFORMATION FOR OFFSHORE EASTERN CANADA

Contract No. OSC83-00030

Submitted to: Royal Commission on the Ocean Ranger Marine Disaster

Submitted by: NORDCO Ltd.

File Ref.: 122-83G

Date: JUNE 1984

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TABLE OF CONTENTS

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EXECUTIVE SUMMARY

The objective of the study undertaken by NORDCO Limited with the assistance from the Centre for Cold Ocean Resource Engineering and the Memorial University of Newfoundland is to critically assess the adequacy of available information on floating ice and structural icing as input to design criteria, operational procedures, and emergency response planning for eastern Canadian offshore exploratory drilling. The study also examines the adequacy of ice hazard detection systems required for safe conduct of drilling operations in the area. The region encompassed by the study extends from the U.S.-Canada border in the south, to the northern limit of the area serviced by east coast ports and where marine drilling systems are used (approximately Lancaster Sound at 75°N). When assessing the adequacy of the ice information, the underlying issue is always human safety.

Icebergs are a significant factor in exploratory operations from the Grand Banks east of Newfoundland, to the northern limit of the study area. The data bases for flux, dimensions, mass, velocity and mechanical properties of icebergs are generally inadequate for definition of extreme events. Operational techniques have been developed that permit exploratory drilling using either dynamically positioned or anchored platforms in the presence of icebergs. These techniques are generally adequate, but improvements are required in the detection of small pieces of ice, both in terms of increased range and for tracking targets through sea clutter in the vicinity of the drilling platform.

The most significant effect of sea ice on exploratory drilling activity in the study area is to limit the operating season. Drilling is currently taking place in two areas where sea ice might be a problem: the Grand Banks during the winter season; and off Labrador during the early part of the summer. Detection of isolated floes under adverse weather conditions is likely to be a problem. However,

information on the mechanical properties of ice under such conditions is sparse, so estimating possible damage to a vessel or drilling platform is difficult.

The data bases for ice loadings due to freezing sea spray and for atmospheric icing conditions (freezing precipitation, supercooled fog, and wet snow turning to ice) is inadequate for calculation of extreme events. The formation and rate of build-up of sea spray ice is a function of vessel shape and size, the shape of the structural members exposed to icing, the nature of the surface coating, and the heat flow through the surface. Although empirical and theoretical models have been developed for the prediction of sea spray icing on vessels, there is very little data on ice accumulation on semi-submersibles. From studies for the Hibernia and Sable Island areas, typical ice loads for such vessels with a 50 year return period may be in the order of 550 tonnes for sea spray icing, with an additional 300 tonnes from atmospheric sources.

Fog and adverse weather conditions are common throughout the east coast exploratory drilling season. Therefore, all weather, day/night ice detection systems are essential from the Grand Banks northwards. Radar is the commonest sensor, but it is evident that floating ice is a poor target, and small pieces of ice cannot be reliably detected using conventional marine radars except under ideal propogation conditions. On-going R & D suggests there is room for improvement in marine radar performance. Airborne ice reconnaissance is often restricted by poor visibility. Imaging airborne radars have proved successful in detecting areas of pack ice, but less so in locating and identifying isolated floes or small icebergs.

Design and construction standards for vessels operating in ice infested waters have been developed by the Classification Societies largely for insurance purposes, and more recently, through the Arctic Shipping Pollution Prevention Regulations. In 1983, Interim Standards for the design, construction and operation of mobile offshore drilling units (MODU's) were issued by the Canadian Coast Guard. However, up to now all exploratory drilling has been restricted to open water

conditions - the only exception being the use of supply vessels for iceberg towing or deflection. Ice management procedures developed in the early 1970's have now become accepted practice and are part of the COGLA guidelines for exploratory drilling.

Several European countries have developed MODU designs for severe weather operations. These designs emphasise covered work areas and, in some cases, flush surfaces to minimise ice accretion. Several of the designs claim to be "ice strengthened", but in the absence of large scale ice impact data, it is difficult to assess the actual capability of such vessels. From the information obtained by the study team, very little attention seems to have been given to the operation of exposed emergency equipment, such as lifeboats, under icing conditions.

Each of the chapters dealing with icebergs, sea ice, icing, ice detection, and the regulatory environment, and with an assessment of the current state of knowledge. These assessments are reproduced below.

<u>Icebergs</u>

(i) Icebergs are a significant factor in exploratory drilling operations from the Grand Banks east of Newfoundland northwards. Although icebergs have been observed in the Gulf of St. Lawrence, they are not considered a serious impediment to drilling in the area. Similarly, south of Newfoundland and off Nova Scotia, icebergs are so rare they are unlikely to interrupt drilling operations.

(ii) The iceberg "season" extends from January to July on the Grand Banks, with the maximum flux occuring in April or May. Further north icebergs occur year round. The minimum flux of icebergs in all areas is between October and December.

(iii) The data bases for flux, dimensions, mass, velocity and mechanical properties are generally inadequate for definition of

extreme events. The best available data bases are for the Grand Banks south of 48°N and the Labrador continental shelf. However, due to difficulties in detecting small bergs the data bases for these areas may be biased towards icebergs larger than 1,000 tonnes. Information on mechanical properties is inadequate everywhere.

(iv) Operational techniques have been developed that permit exploratory drilling using either dynamically positioned or anchored platforms in the presence of icebergs. These techniques are generally adequate, but improvements are required in the detection of small pieces of ice, both in terms of increased range and for tracking through sea clutter in the vicinity of the drilling platform. The early detection of icebergs representing a hazard to anchored platforms, is essential to their safe operation as lead times for moving such platforms is significantly greater than for the dynamically positioned systems.

(v) Research on the impact forces between icebergs of various sizes and exploratory drilling platforms, particularly as might occur with severe sea states is in its infancy. Progress is hampered by lack of knowledge of the maximum velocities small pieces of ice might attain, mechanical properties of the ice, and its behaviour in impact situations.

(vi) The presence of isolated growlers can present a hazard to supply vessels, particularly if the vessel is moving at its normal cruising speed on the assumption of ice free conditions. Ice strengthened vessels are generally used from the Grand Banks north, but the degree of strengthening is unlikely to be sufficient to ensure the safety of the vessel if it is travelling at high speed at the moment of impact. Neither radar nor visual detection of growlers is reliable under the prevailing weather and sea conditions off the east coast.

Sea Ice

(i) The most significant effect of sea ice on current drilling activity within the study area is to limit the drilling season.

(ii) Current operating procedures call for the drilling unit to move off location if sea ice is threatening.

(iii) Drilling is currently taking place in two areas where sea ice is likely to be a problem. These areas are the Grand Banks in winter and off the Labrador coast in the early summer.

(iv) The two situations identified where the danger from sea ice would be the greatest are: (a) collision with an isolated floe drifting ahead of the main pack during a storm situation and (b) sea ice drifting into the drilling area in a situation when the unit could not move off site.

(v) There is insufficient data available to define the risks associated with (iv).

(vi) The data base for many sea ice parameters is not sufficient to define the effects of an impact.

Icing

(i) The database on ice loadings from sea spray is limited and does not permit the accurate calculation of "100 year events".

(ii) Empirical and theoretical models have been developed for the prediction of sea spray icing on vessels, but comparisons suggest that results reflect the type of vessel studied in the particular database and are not transferable to significantly different types of vessel.

(iii) Using an empirical formula plus environmental data, the occurrence of moderate or severe sea spray icing conditions is

estimated to occur 8% of the time for the Sable Island area and 9.5% to 12.5% at Hibernia during the most severe month - February in both cases. Only general information in the form of maps appears to be available outside these two areas.

(iv) Formation and rate of build-up of sea spray ice is a function of vessel shape and size, the shape of structural members exposed to icing, the nature of the surface coating, and the heat flow through the surface. Therefore, most regulatory authorities give no guidance on ice build-up and limit themselves to specifying the maximum allowable ice accumulation to be used in stability calculations.

(v) Icing data for semi-submersibles is virtually non-existant, and there is no clear understanding of ice accumulation on the underside of deck areas, or on changes in accumulation rates up the sides of vertical or inclined columns.

(vi) The database for atmospheric icing events (freezing precipitation, supercooled fog, and wet snow turning to ice) is not sufficient to calculate meaningful "100 year events".

(vii) There are indications that for some areas the accumulation of ice on drilling platforms due to freezing precipitation may be as important as the accumulation from sea spray.

(viii) Some of the operating manuals reviewed in the course of this study make no reference to icing of any type, whereas others detail actions to be taken, including load dumping priorities.

(ix) Total icing loads with a 50 year return period in the Hibernia area have been estimated to be 550 tonnes from sea spray icing, with a maximum load, taking into account atmospheric icing, of about 830 tonnes. However, these values depend heavily on a number of rig parameters and the model used to estimate extent and rate of accumulation of ice.

(x) A formal record of ice build-up on drilling platforms at different locations and operating under different environmental conditions is urgently required.

Ice Detection

(a) Icebergs

(i) Icebergs of any size are poor radar targets.

(ii) The presence of clutter, especially sea clutter, is the major limiting factor in the detection of icebergs when at ranges shorter than the maximum. This presents a serious problem in the detection of bergy bits and, in particular, growlers, as they are normally only detected at short ranges, and even in low to moderate sea states the clutter may be sufficient to mask them at their maximum ranges.

(iii) In the absence of clutter there is a direct relationship between the size of the iceberg and the maximum range of detection. The tremendous scatter in the range of detection data provided by the various researchers suggests that caution is necessary in applying the relationship.

(iv) Subnormal propagation conditions dominate in the Grand Banks region. There is very little information available regarding the conditions in the more northern areas. There is a need for more quantitative information for all areas.

(v) The level of on-going R&D indicates there is recognition of the need for improvement in marine radar for the detection of icebergs.

(vi) None of the research reported here provided significant information on the number of icebergs not detected at all on marine radar. This has created the false impression that only small targets in clutter go undetected. However, it has been the

experience of marine interests in these waters that quite frequently icebergs of almost any size and at moderate ranges do go undetected. This is difficult to quantify but the need exists to determine the percentage of time and the conditions under which this situation might occur.

(vii) Given the predominately poor visibility conditions, particularly on the Grand Banks, there is some question regarding the effectiveness of airborne visual reconnaissance.

(viii) Long range visual reconnaissance by surface vessels will also be restricted by the poor visibility and the short coverage area observed at any given time.

(ix) The effectiveness of short range visual reconnaissance by support vessels in the vicinity of a drilling platform at times of low visibility or in darkness is unknown. Larger ice targets may be detected but growlers may still not be sighted under these conditions. During rough sea conditions the movements of the support vessel may be restricted, reducing its capability to perform reconnaissance work when it is most needed.

(x) SLAR, because of its all weather, day/night capability, has the potential of being a very valuable reconnaissance tool, but there is considerable confusion regarding its true detection capability against essentially point targets. As with marine radar this capability needs to be quantified.

(xi) A major limitation with SLAR is the problem of identifying targets. In areas such as the Grand Banks there is significant fishing and marine transport traffic. Thus, the probability of false alarm is significant, at least in this region.

(b) Sea Ice

(i) The detection range for sea ice floes appears to be similar to that for small icebergs and growlers. Signal processing techniques and high antenna heights have been shown to improve topographic feature detection ranges for consolidated pack ice in the Beaufort Sea, but this may not apply for the East Coast of Canada.

(ii) Because unconsolidated or loose pack ice may take on the appearance of sea clutter on marine radar it may be difficult to detect under certain conditions.

(iii) The inability to identify ice types in the sea ice pack using marine radar may prevent detection of potential dangerous multi-year floes.

(iv) Because pack ice is generally a large scale phenomena, visual observations, either from ship or aircraft, should be adequate for monitoring it, and poor visibility should not present a major problem. The detection of multi-year floes should also be possible but well trained observers will be required.

(v) The almost all weather day/night reconnaissance capability of SLAR makes it an ideal instrument for the reconnaissance of sea ice. It is also capable of providing classification of ice types and accurate positional information.

(c) General Considerations

(i) Individually, each detection method has its shortcomings. The performance achieved through an integration of all the techniques may be adequate but there is insufficient evidence to make an accurate quantitative assessment. For long range strategic reconnaissance upstream of a drill site, it would appear that the combination of both airborne and ship based visual reconnaissance along with SLAR might be adequate. However, SLAR would have to be

employed on a dedicated basis rather than as a tool of opportunity employed by another agency. With the integration of all these methods, however, small and dangerous targets may still slip through undetected.

ii) For short range close tactical monitoring there are a number of problems. Under moderate sea conditions, with even moderate to poor visibility in daylight, the combined use of marine radar and diligent visual reconnaissance (from the drilling platform and service vessels) should make it possible to detect and keep track of all ice hazards. Under severe low visibility weather conditions and in darkness, visual reconnaissance will be impossible. Marine radar will have to be relied upon almost totally. Unfortunately, marine radar is least reliable under severe weather conditions and ice hazards may approach undetected. As noted earlier, it should be relatively easy to track sea ice and this is applicable even at short ranges from the drilling platform. The problem at close range is that small icebergs, growlers, multi-year floes, etc., within the sea ice pack may go undetected when reliable detection and precise positional information is most necessary. The presence of darkness, low visibility and/or rough seas will compound this problem.

Regulations

(i) Design and construction standards for vessels operating in ice infested waters have been developed by Classification Societies, largely for insurance purposes. The Arctic voyage of the "Manhattan" in 1969 was closely followed by promulgation of the Arctic Waters Pollution Prevention Act, and the accompanying Arctic Shipping Pollution Prevention Regulations. These regulations, for the first time, specified the design and construction standards required for vessels operating north of 60°N latitude within 100 miles of the Canadian coastline. These regulations apply to exploration activity north of 60°N latitude - including the dates of entry and exit from these waters for

different ice class vessels. The design regulations do not specifically refer to MODU's.

(ii) The Interim Standards for the design, construction and operation of MODU's recently issued by the Canadian Coast Guard, generally require ice loadings to be calculated for 100 year return events. However, as is evident from this study, there is not sufficient information on most ice parameters to calculate realistic 100 year events.

(iii) All exploratory drilling vessels operating in the vicinity of floating ice have sophisticated ice management systems, with clearly defined operating procedures should approaching ice pose a hazard to the operations. However, these management systems rely on detection of hazardous ice and it is doubtful whether present technology is adequate for detection of small bergy bits and growlers under adverse weather conditions.

(iv) A number of theoretical studies have been carried out in order to estimate the damage a small, undetected piece of ice is likely to inflict on a MODU. Recent laboratory experiments indicate the energies involved may be significantly greater than those assumed by Classification Societies for supply boat collision with a MODU. However, the collision forces are dependent on the behaviour of the ice on impact and there have been no large scale experiments to verify the theoretical assumptions. Such experiments are needed to determine damaged stability requirements for MODU's, as well as strengthening requirements when contact with floating ice is likely to be a common occurrence.

(v) Several European countries have MODU designs for severe weather operations. The advantages of such vessels are flush surfaces to minimize structural icing and covered work and emergency assembly areas. Several of these designs have "ice strengthening", but it is not clear how effective such re-inforcing would be in the event of a collision with glacial ice.

(vi) Very little consideration appear to have been given to the operation of exposed emergency equipment, such as lifeboats and liferafts, under freezing spray or precipitation conditions. Also, it is not clear from regulations whether lifeboats or liferafts could operate in loose pack ice without a significant risk of hull puncture.

1.0 INTRODUCTION

1.1 Terms of Reference

The Terms of Reference of the Royal Commission on the Ocean Ranger Marine Disaster call for two major activities. Part I, an extensive investigation into the loss of the Ocean Ranger, and Part II, which calls for the Commission to "inquire into, report upon, and make recommendations with respect to" both marine and drilling aspects of practices and procedures in respect of Eastern Canada Offshore drilling operations and to a number of specific matters relating to drilling units operating offshore.

The geographic area for the Part II studies (Figure 1.1) extends from the shoreline to the limit of jurisdictional claims, and from the Canada-U.S. boundary to the northern limit of the area serviced by east coast ports and where marine drilling systems are used (approximately Lancaster Sound at 75^{o}N). The study plan has been divided into five areas: environment, regulation, design, safety and training. In each case, the studies encompass offshore exploration and delineation drilling operations, including service and supply (marine and air) activities. The issue, in all cases is human safety, with property safety only being considered to the extent it affects human safety.

On 17 May, 1983 NORDCO Limited and C-CORE were invited by the Royal Commission to submit a work plan to address the "ice" aspects of the environmental group of studies. The study objectives being to critically assess the adequacy of available information on ice needed as input to design criteria, operating constraints, and emergency response capabilities for Eastern Canada exploratory drilling operations. The study was also to critically assess the adequacy of ice hazard detection systems required for safe conduct of Eastern Canada Offshore drilling operations.

The Royal Commission in its invitation defined key terms of the required study as in Table 1.1.

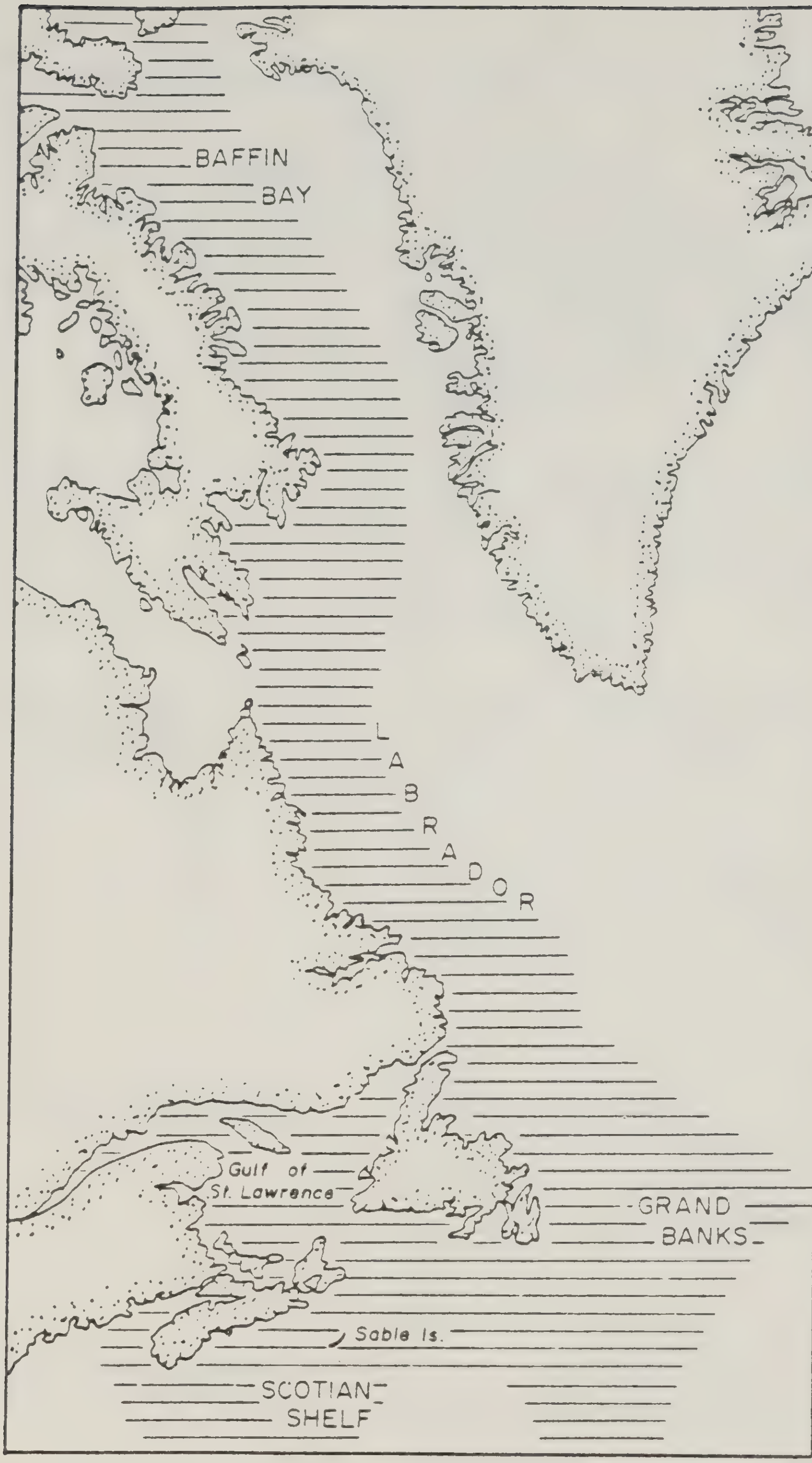

FIGURE 1.1 Royal Commission on the Ocean Ranger Marine Disaster - East Coast Offshore Study Area

Table 1.1
Definition of Terms

Ice	To include ice in all its forms: sea ice, icebergs, (including scour effects), freezing spray and ice accretion.
Design Criteria	Refers to mobile offshore drilling units (dynamically positioned drillships, semi-submersibles and jack-up units).
Operating Considerations	Includes conditions for: - rigs (transfer, drilling and survival modes) - vessels (standby, transport, loading and offloading) - helicopters (take-off, landing and travel)
Emergency Response Capability	Refers to equipment and procedures used for personnel evacuation, survival, location, and recovery, and includes Government Search and Rescue.
Ice Hazard Detection Systems	Refers to equipment (hardware and software), personnel, and procedures used to detect and forecast hazards presented by ice and will include the measurement/estimation of driving forces (wind, currents).

1.2 Canadian East Coast Offshore Operations

The area of concern extends some 3000 km from the United States border in the south, to Lancaster Sound at the entrance to the Northwest Passage. The climate varies from temperate to Arctic. The width of the continental shelf to the 200 m isobath varies from 200 km off Nova Scotia to 400 km southeast of Newfoundland. Further north off Labrador the shelf break generally occurs at 300 m and 150 km from the coast. East of Baffin Island there is virtually no shelf and the seabed plunges to depths of 1000m within 50m km of the coast.

Exploration permits, reflecting current knowledge of sedimentary basin structures on the east coast, have been awarded for parts of the Gulf of St. Lawrence, large parts of the Scotian Shelf (particularly near the shelf break), the eastern and northern Grand Banks, northeast of Newfoundland and along the coast of Labrador. The only permit areas off Baffin Island are at the latitude of Davis Strait and at the entrance to Lancaster Sound (Figure 1.2). To date drilling has been restricted to the open water season, and the type of rig employed has been dictated by the water depth, wave conditions,and the need for mobility in the path of icebergs.

Three forms of "ice" are encountered in the study area: glacial ice in the form of icebergs; sea ice; and ice that forms on structures exposed to freezing precipitation or spray. Up to now, exploratory drilling on the east coast has not been attempted in the presence of sea ice, but has become routine in the presence of icebergs. Super-structure icing, although recognized as a problem for fishing vessels operating in the area during the winter months, has only recently been addressed as a significant concern for offshore drilling operations.

A further hazard on the east coast related to floating ice is the possibility of an iceberg keel dragging across the drillsite (after the drilling vessel has moved off) and damaging equipment on the seabed. However, such an event is unlikely to constitute a risk to human safety, and therefore has not been included in the study.

FIGURE 1.2

EXPLORATION PERMIT AREAS
(COGLA 1983)

Region	Drilling Operation		Ice Hazard Level		
	Rig Type	Season (months)	Icebergs	Sea Ice	Icing
Lancaster Sound	DP	3	3	2	3
Baffin Bay	DP	3	3	1-2	3
Labrador	DP	3-5	3	1-2	2-3
N.E. Nfld.	An	8-12	3	1	2-3
Grand Banks	An	12	1-2	1-2	2-3
Scotian Shelf	An/J	12	0	0	2-3
Gulf St. Lawrence	An/J	8	0	1	1-2

Notes: DP - dynamically positioned drillship or semi-submersible

An - anchored drillship or semi-submersible

J - jack-up drilling platform

Ice hazard level: 3 severe; 2 moderate; 1 slight; 0 negligible

Table 1.2 Summary of ice hazard level by region assuming drilling is restricted to the "open water" season.

Given the requirements for open water conditions, year round drilling has only been possible off Nova Scotia and, with due attention to icebergs and occasional incursions of sea ice, on the Grand Banks (Table 1.2). Further north, the sea is covered by ice during the winter and exposed to southward drifting icebergs throughout the year. Nevertheless, drilling using dynamically positioned drillships has become routine during the summer months as far north as Davis Strait. In the extreme north, off Lancaster Sound, drilling permits have been sought, but actual drilling has not yet commenced.

Jack-up systems (Figure 1.3(a)) have been used in the Gulf of St. Lawrence and in the shallow waters close to Sable Island off Nova Scotia. Elsewhere off Nova Scotia and on the Grand Banks of Newfoundland, anchored semi-submersibles are used (Figure 1.3(b)). Off Labrador and in Davis Strait dynamically positioned vessels, generally drillships, have been used to meet the need for mobility in the path of icebergs (Figure 1.3(c)). None of the drilling vessels used so far on the East Coast have been "ice class", although some of the semi-submersibles have extra strengthening in their vertical columns. Hence, operations depend on detection of all potentially hazardous floating ice in sufficient time to either deflect the ice, or to move the drilling vessel out of the path of the ice. Supply boats (Figure 1.3(d)), particularly those used off Labrador, are often ice class, such as Lloyds Arctic Class 2 or 3. This is necessary as the supply vessels are often required to work in close proximity to icebergs for towing purposes, or actually in contact with small pieces of ice when they have to be deflected away from the drilling vessel.

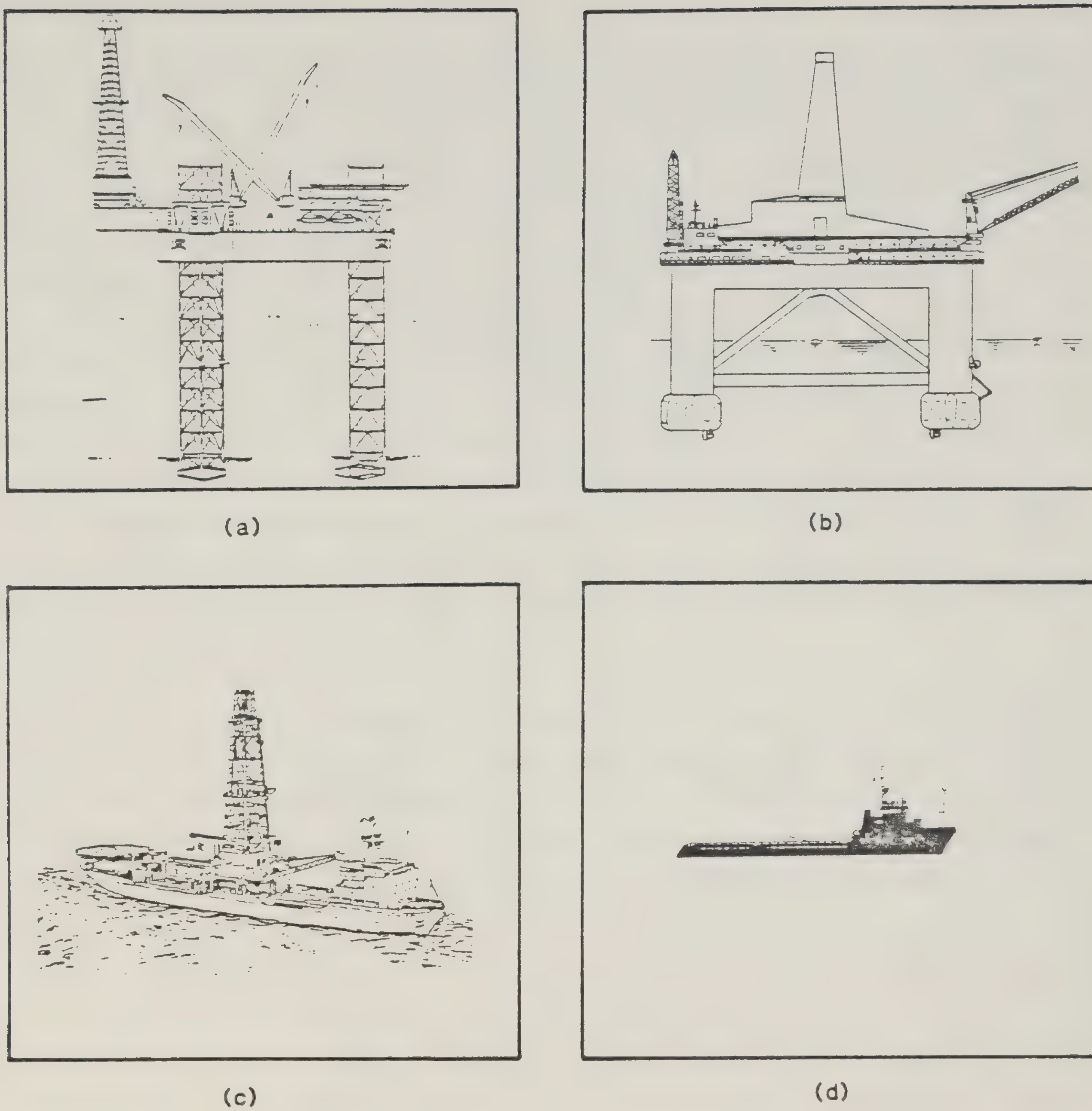

FIGURE 1.3 Typical drilling platforms and vessels in use off Eastern Canada. (a) Jack-up, (b) semi-submersible, (c) drillship, and (d) supply vessel.

1.3 Organization of Study

The following four chapters dealing with icebergs, sea ice, icing, and ice detection, start with a brief introduction outlining the importance of the chapter subject in exploratory drilling off the east coast of Canada. In each case, the introduction is followed by a review of the information available to the study team (Table 1.3) on the particular topic of concern, and then by a discussion of the impact the current state of knowledge has on drilling practice in various parts of the east coast offshore. Each chapter ends with an assessment of the current state of knowledge and comments on current practice for the respective subject areas. Statistical and technical discussions and conclusions are contained within the review sections, and the assessment sections are, in each case, a statement of the main points to emerge from the technical review in a form suitable for non-specialist readers requiring a general appreciation of the state of the art.

Chapter six is a review of the "ice" sections of various government design, construction, and operational regulations relevant to east coast offshore exploratory drilling. Comments are based on the study team's appreciation of the current state of knowledge regarding icebergs, sea ice, icing and ice detection as portrayed in the earlier chapters.

STUDY TEAM

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Consultants

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Centre for Cold Ocean Resources Engineer	J. Whittick

Table 1.3: Studv Personnel

1.4 Information Sources

This section and the bibliography have been prepared by the Ocean Engineering Information Centre (OEIC) and the NORDCO Ltd. study team.

After discussion with representatives of NORDCO and the Commission, information was provided by OEIC to the individual(s) responsible for each section of the report. Different search procedures were carried out for each section as not all methods were applicable to every section. The appropriate search procedures and relevant information sources to be checked were selected after a review of sources with the NORDCO researchers.

First, major sources of "ice" information were identified, then these sources were checked for relevant "ice" data in relation to offshore drilling procedures for offshore Eastern Canada and relayed to the researchers. "Non-document" and proprietary sources to be followed were identified early in the study, as these sources often require substantial lead time before access to the material can be obtained. Sources from U.K., U.S., Norway and Canada were checked for both ongoing research and for document data.

Information either by bibliographic listings or by supplying physical documents was provided to the researchers at NORDCO for review. Subsequently, OEIC indexed documents/projects identified by the NORDCO study team which pertained to the project.

Ice Conditions

A computer search was not undertaken, as the relevent documents describing the ice conditions for the Canadian east coast were either in the OEIC collection or NORDCO files. Emphasis was placed on the identification of major review documents and the search was broken down into four main sections:

(a) Atlases;

(b) Bibliographies;

(c) Environmental impact statements; and

(d) Industry reports.

All major atlases covering the study area and bibliographies referencing ice conditions in the east coast were identified. OEIC and BIO (Bedford Institute of Oceanography) holdings were checked for relevant initial environmental assessments and environment impact statements. Pallister Resource Management documents and Arctic Institute (ASTIS Bibliography) were also checked as the former is the main distribution point for Canadian offshore industry documents, and the latter is responsible for their indexing.

The following EIS and IEA sources were identified:

i) Nova Scotia - Mobil Oil Venture EIS;

ii) Prince Edward Island - two contingency plans located, but no EIS; main sources identified were Black's work, McGill University Marine Sciences Centre and BIO publications;

iii) Strait of Belle Isle - Lower Churchill EIS;

iv) North East Grand Banks - Mobil and Petro Canada;

v) Offshore Labrador - Petro Canada IEA; Texaco sites;

vi) Eastern Arctic Marine Environmental Study

vii) Eastern Arctic Offshore Drilling - Southern Davis Strait
- EAMES
- EIS by Imperial Oil Ltd.;

viii) Eastern Arctic Offshore Drilling - Northern Davis Strait and Baffin Bay;

ix) Lancaster Sound - Norlands and subsequently Consolidex
- DIAND Lancaster Sound Study;

x) Arctic Pilot Project;

xi) Beaufort Sea EIS - (Transportation documents only); and

xii) "Sea Ice Management" Seminar, Memorial University of Newfoundland, November 1983.

Industry reports filed with COGLA and DIAND were identified and bibliographies available from these were listed, but the individual reports were not.

The OEIC index was also checked under all geographic terms including Greenland and the researcher at NORDCO notified of the listing. Material was then selected by the researcher at NORDCO and OEIC indexed the identified documents.

Ice Detection

A computer search was undertaken on three data bases covering literature from 1978 to date. These were:

a) COLD (Cold Regions Research and Engineering Laboratory);
b) NTIS (National Technical Information Service); and
c) RESORS (Canada Centre for Remote Sensing)

A computer list was provided and subsequently relevant documents were also provided. OEIC then indexed those documents which pertained to the project.

Ice as a Factor in Design

The OEIC collection concentrates on offshore structure designs but does not cover vessel design. All codes, regulations, guidelines, and legislation held by OEIC were checked for relevant sections on ice. This search also covered the identification of material pertaining to ice as a factor in offshore operations. The certification authorities identified to be checked were:

- American Bureau of Shipping;
- American Petroleum Institute;
- Bureau Veritas;
- Det norske Veritas;
- Germanischer Lloyd;
- Lloyd's Register of Shipping; and
- IMO.

Legislation for U.K., Norway and Canada were checked and references to "ice" were flagged. Cards were also produced for those references checked and in which no reference to ice data was found.

OEIC also requested that RCORMD Information Centre produce a listing of their standards, codes, regulations and legislation. This listing was sent directly to NORDCO. OEIC checked the RCORMD Bulletin for material not indexed by their listing but which might be relevant to design and operations. It was recommended after discussion that no computer search be undertaken as the majority of the literature on "ice design" pertains to the high arctic and a computer search would only produce a huge volume of irrelevant literature. Documents on a major Norwegian project undertaken by a number of companies "Marine Ships and Structures in Ice" was provided to the researcher for review.

Ice as a Factor in Operations

In "ice/operations", many of the same sources as for the "ice/design" section was used. Operational manuals held at the Commission were also checked. A manual search of Ship Abstracts (covering Scandinavian and the British literature) and Offshore Abstracts (covering British and U.S. literature) was undertaken. Few references to "ice" in operations were identified. A major program undertaken by Norway SPS (Offshore Safety) was identified but OEIC was not able to ascertain if this was relevant. A second source from Norway, a conference entitled Winter Drilling in the North was also identified (the papers are in Norwegian).

Contingency plans for wellsites and/or operators were identified through the RCORMD and COGLA office using the recent bibliography produced by COGLA. Not all contingency plans for each wellsite were located.

Ice as a Factor in Emergency Situations

A computer search on the following data bases were carried out:

a) NTIS (National Technical Information Service covering U.S. government documents)'

b) COLD (U.S. Army Cold Regions Research and Engineering Laboratory data bases); and

c) OOT (Transport Canada data bases).

References were pulled out under "Search and Rescue" and "Emergency" response. Limiting the search with the term "ice" found few references. Manual searches were also undertaken on:

a) Ships Abstracts (indexing Scandinavian and British sources);
b) Oil Index (produced by the Norwegian Petroleum Directorate);
c) MRIS (Maritime Research Information Service covering U.S. literature);
d) Transportation Development Centre (TDC) - listing of Canadian Marine R & D projects
e) Arctic Sciences and Technology Information Service (ASTIS);
f) Major Offshore Technology conferences OTC, EUROPEC, Offshore North Seas, and POAC;
g) University Library Collection - only IMO documents found relevent;
h) Norwegian Petroleum Directorate - Regulations;
i) R & D Bulletin (produced by DSS) - last 12 months; and
j) Offshore Abstracts (IRL covering British and U.S. material).

Very few references were found in relation to ice. Those found on the COLD data base related to "avalanches" and snow problems. A recent document on the "evaluation of search and rescue in Canada" was checked but no reference to ice was identified.

2.0 ICEBERGS

2.1 Introduction

Exploratory drilling for oil and gas in the presence of icebergs has become a routine activity in the study area. From the Grand Banks to Davis Strait drillships and semi-submersible drilling platforms (dynamically-positioned or anchored) have successfully completed wells in areas frequented by icebergs.

The basic methods used for dealing with the icebergs have remained unchanged since they were developed in the early 1970's. These include: detecting the iceberg, predicting its future drift, attempting to deflect it if it is threatening the unit, and moving the drilling unit if deflection is unsuccessful.

The potential for collision between a drilling unit and an iceberg exists if the iceberg is not detected in time to move the unit, or if deflection is not possible, and the unit is unable to move off the site for some reason. The remainder of this chapter presents an overview and assessment of the data necessary to estimate the risk of such a contact and to evaluate the potential results of any impact.

2.2 Summary of Information Available

2.2.1 Distribution and Flux

The glaciers of West Greenland are the source of nearly all icebergs in the study area. Each year tens of thousands of icebergs calve from these glaciers but only a fraction of these find their way out of the fjords of West Greenland and into Baffin Bay. Out of the thousands of icebergs that enter Baffin Bay each year only a few hundred will complete the 3000 kilometer journey south to the Grand Banks (Figure 2.1).

The icebergs that do reach the Grand Banks follow the Labrador current south along the Baffin and Labrador coast and then split into

an inshore and offshore branch south of 49°N. The inshore branch flows south through the Avalon Channel while the offshore branch follows the eastern edge of the Grand Banks. Although the offshore branch is generally more important, there are major seasonal and annual variations in the importance of the two branches. One locally significant variation in the annual iceberg flux is the movement of icebergs into the Gulf of St. Lawrence through the Strait of Belle Isle. Although it is rare for icebergs to enter the Gulf in any significant numbers there is evidence to indicate that as many as 100 icebergs have entered the Gulf during a single year (International Ice Patrol, 1962).

Data on the spatial pattern of iceberg distribution is available from the following sources: Trofimenkoff (1978); Gustajtis and Buckley (1977); and Markham (1980).

Estimates of iceberg distribution and flux are based on two main data sources. For the Grand Banks area, flux estimates are normally based on ship and aircraft sightings compiled by the International Ice Patrol (IIP) over the last 70 years. For areas north of 50°N, estimates are normally based on data from a series of special flights carried out by the IIP during the 1960's and 70's. The majority of these northern flights were carried out during the months of December through March with only occasional flights outside this period. Due to the problems associated with sighting small targets from aircraft and ships (see Chapter 5) both data sets underestimate the population of small icebergs, bergy bits, and especially growlers.

The mean annual iceberg flux across each degree of latitude from 40°N to 67°N is presented in Figure 2.2. This figure includes estimates from several different sources. The estimate by Anderson (1971) is based on IIP data from the years 1963 to 1969. This period had a lower then normal average flux across 48°N which accounts for the difference between this estimate and that of Blenkarn and Knapp (1968). The two remaining curves are attempts to update Anderson's

information with more recent data. This figure clearly demonstrates the degree of uncertainty in iceberg flux estimates for latitudes north of 48°N.

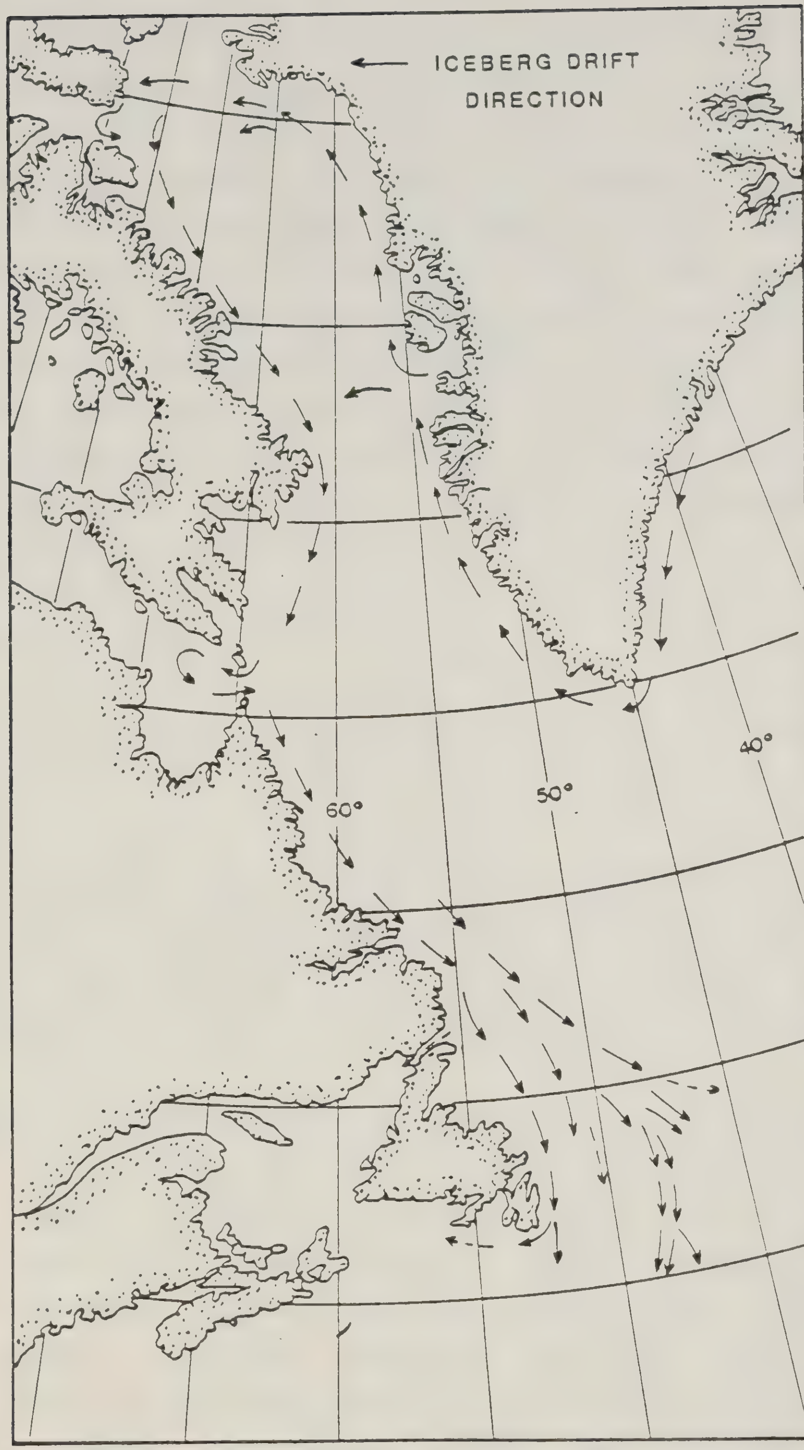

FIGURE 2.1 General direction of iceberg drift

Analysis of the seasonal variation in icebergs flux (Figure 2.3) indicates that the maximum normally occurs in April and May on the Grand Banks, in May off Labrador and in July in Baffin Bay. The minimum flux occurs in October, November and December in all areas. Analysis of data for the Grand Banks indicates that the peak flux can occur as early as March or as late as April. The annual variations in iceberg flux across 48°N have been documented by the IIP since the late 1800's. These statistics are presented in Figure 2.4. The most significant aspect of the annual flux is its extreme variability ranging from 0 to greater than 1500. It is evident that there is considerable variation in the pattern, timing and intensity of the iceberg flux through the study area.

2.2.2 Dimensions and Mass

The dimensions and mass of an iceberg will have a direct impact on:

(a) the ability to detect the iceberg either visually or with radar;
(b) the strategy that can be used to deflect the iceberg;
(c) the response of the iceberg to various environmental forces, and;
(d) the impact that the iceberg will have on an offshore platform.

The bulk of the available iceberg observations, including most of those from the IIP, do not provide reliable estimates of iceberg dimensions but simply classify icebergs into one of six size catagories (see Table 2.1). The principal source of data on iceberg dimensions off the east coast are the observations made by oil companies in support of their offshore drilling programs. These observations are normally carried out in the vicinity of wellsites but some measurement programs have been carried out in other areas to

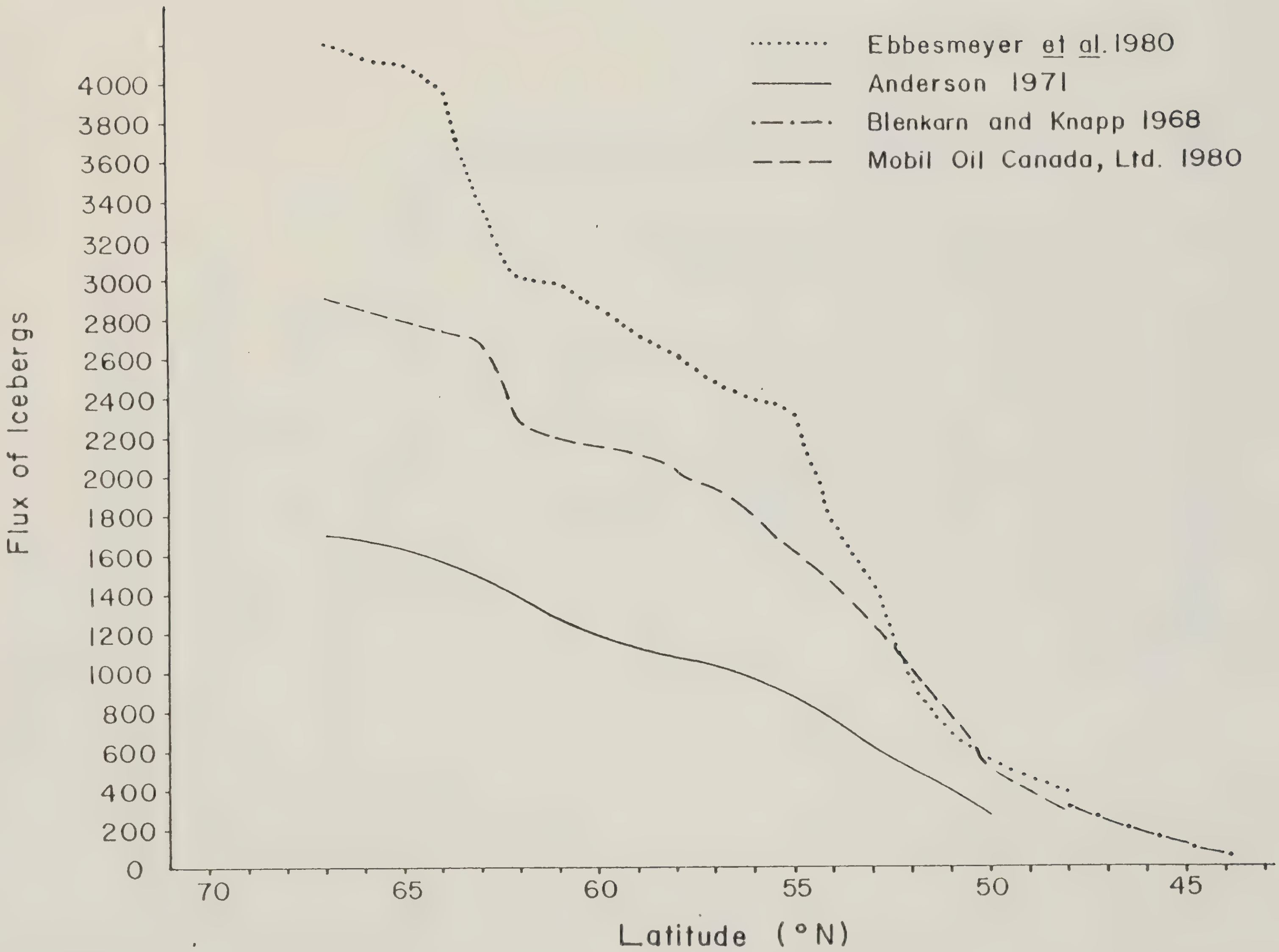

FIGURE 2.2 Mean annual iceberg flux by latitude

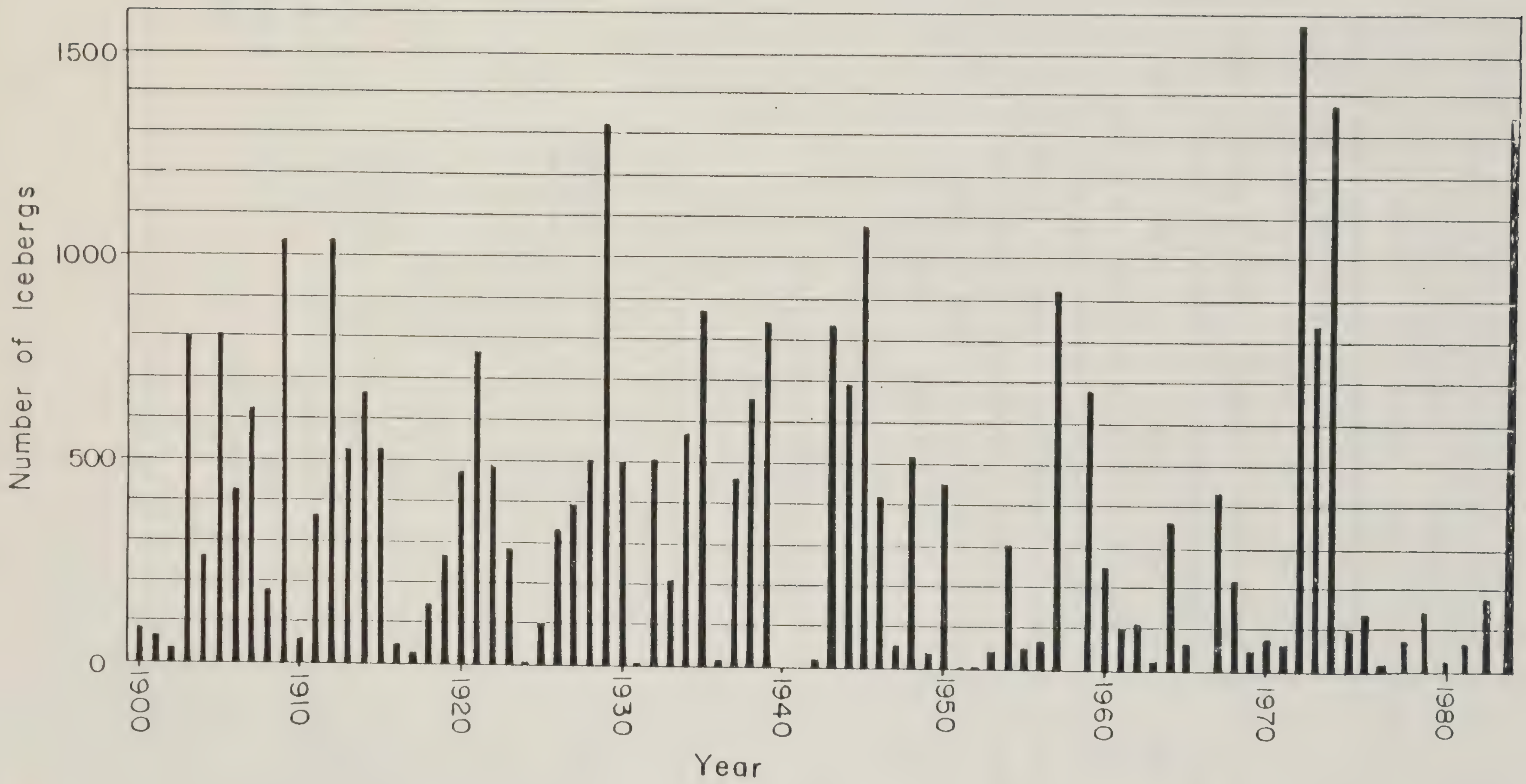

FIGURE 2.4 Number of icebergs crossing latitude 48°N from 1900 to Spring, 1983 (Ketchen 1977 Updated with Annual IIP Reports and Pers. Comm. IIP)

collect baseline data. Due to a number of reasons, the data is often biased towards the larger icebergs and does not accurately represent the population of growlers and bergy bits. To reflect this lack of data for small icebergs most statistical summaries are limited to icebergs larger than 1000 tonnes.

The method normally used to measure the above water dimensions of an iceberg is to use a sextant to measure angles in conjunction with ranges obtained from radar or a visual range finder. The mass of the iceberg can then be estimated using formulae which take into consideration the dimensions and shape of the iceberg, or by more detailed photographic methods. In some cases stereoscopic aerial photography has been used to estimate iceberg mass. Iceberg draft is normally measured using a side scan sonar or estimated based on the density of ice and the icebergs above water geometry.

Table 2.1
Iceberg Size Categories
(Murray, 1968)

Type	Height (metres)	Length (metres)	Approx. Mass (tonnes)
Growler	1	6	200
Bergy Bit	1-5	6-20	200 - 7000
Small Iceberg	6-15	21-60	7000-200,000
Medium Iceberg	16-45	61-122	200,000 - 2.5M
Large Iceberg	46-77	123-213	> 2.5M
Very Large	78+	214+	

The frequency distribution of iceberg mass for different regions is presented in Figure 2.5. The data can be summarized as follows:

(a) The curve for the northern coast of west Greenland is included since this is the source area for many east coast icebergs;

(b) The data for Baffin Bay/Davis Strait is for a single year and should be used with caution;

(c) The Labrador curve should be the most reliable since it is based on a large data set from a number of sites and over a number of years;

(d) The curve for the northeast part of the Newfoundland shelf is based on three years of data, all of which were severe ice years;

(e) There are no summaries of iceberg mass based on measured data available for the Grand Banks, therefore two estimated curves for this area are included. The curve developed by Hotzel and Miller (1983) is estimated from measurements of iceberg water line cross-sectional area carried out by the International Ice Patrol (1976).

(f) There are no data available for the Scotian Shelf and Gulf of St. Lawrence areas. Analysis of the frequency distribution for these areas is hampered by the infrequent occurrence of icebergs.

The curves presented in Figure (2.5) only represent icebergs with a mass greater than 1000 tonnes. Statistics on the frequency of 'icebergs' smaller than this size are extremely limited. In general the review of the literature indicates that very little is known of the frequency and distribution of growlers and bergy bits. Due to the problems of identifying these small targets either visually or with radar they are under represented in almost all data sets. Data from drilling sites indicate that growlers are frequently not observed even when they are closer than 10 km, and they are not always included in the statistics when they are observed.

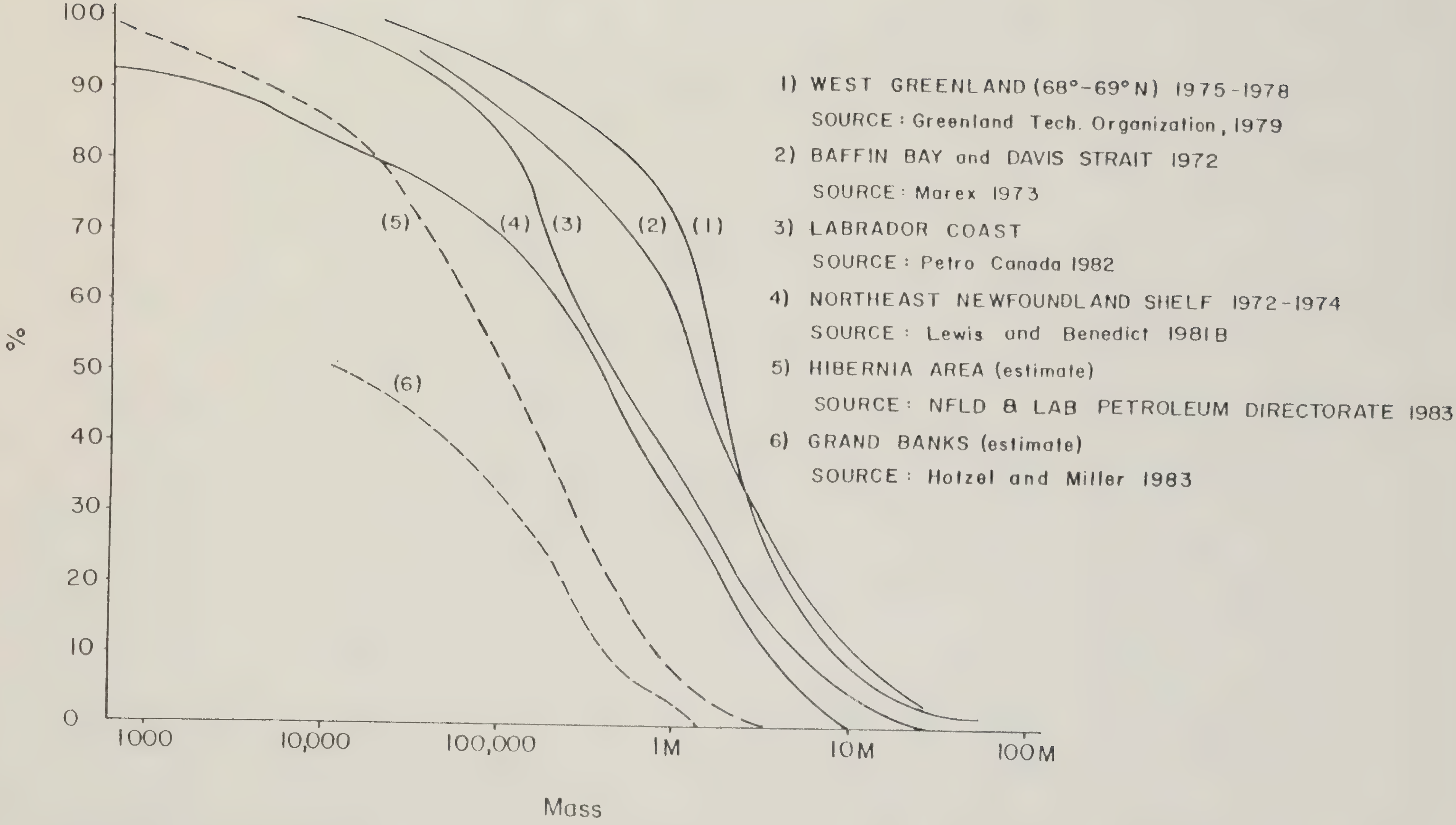

FIGURE 2.5 Percentage exceedence of iceberg mass

The data set for most regions is not sufficient to identify annual variations in the size and mass distributions but there are indications that the frequency of larger icebergs is higher in heavy iceberg years. This is not surprising since heavy iceberg years are normally heavy pack ice years which would tend to reduce the decay of icebergs and therefore increase the mean size. This effect would be most strongly felt near the southern limits of iceberg distribution.

The concept of the maximum credible size of iceberg is often discussed in the literature but recent work of the Newfoundland and Labrador Petroleum Directorate (1983) indicates that this may not be an important design factor. The maximum credible iceberg has a very low probability of occurrence, even lower probability of impacting a structure and practically no probability of doing so at any considerable speed. If the probability of impact is held constant the maximum energy level is associated not with the maximum credible iceberg but with a much smaller iceberg travelling at higher speeds. The risk from the maximum credible iceberg is further reduced by the higher probability that it would be detected and tracked.

The available curves on the frequency distribution of iceberg length and draft are presented in Figures 2.6 and 2.7. There is less published data available for these parameters than for iceberg mass, although the raw data must exist. Iceberg length is an important factor in iceberg detection and is required to calculate the probability of impact. Iceberg draft measurements are needed to calculate the grounding depths of different size icebergs. It is important to note that the iceberg draft distribution is limited by the water depth.

2.2.3 Iceberg Drift Speeds

The speed of an iceberg is governed by a number of factors, but the wind and current velocities are normally dominant for large icebergs. Since wind and especially current conditions can vary considerably over short distances, significant variations in iceberg velocity can occur over distances less than 10 km.

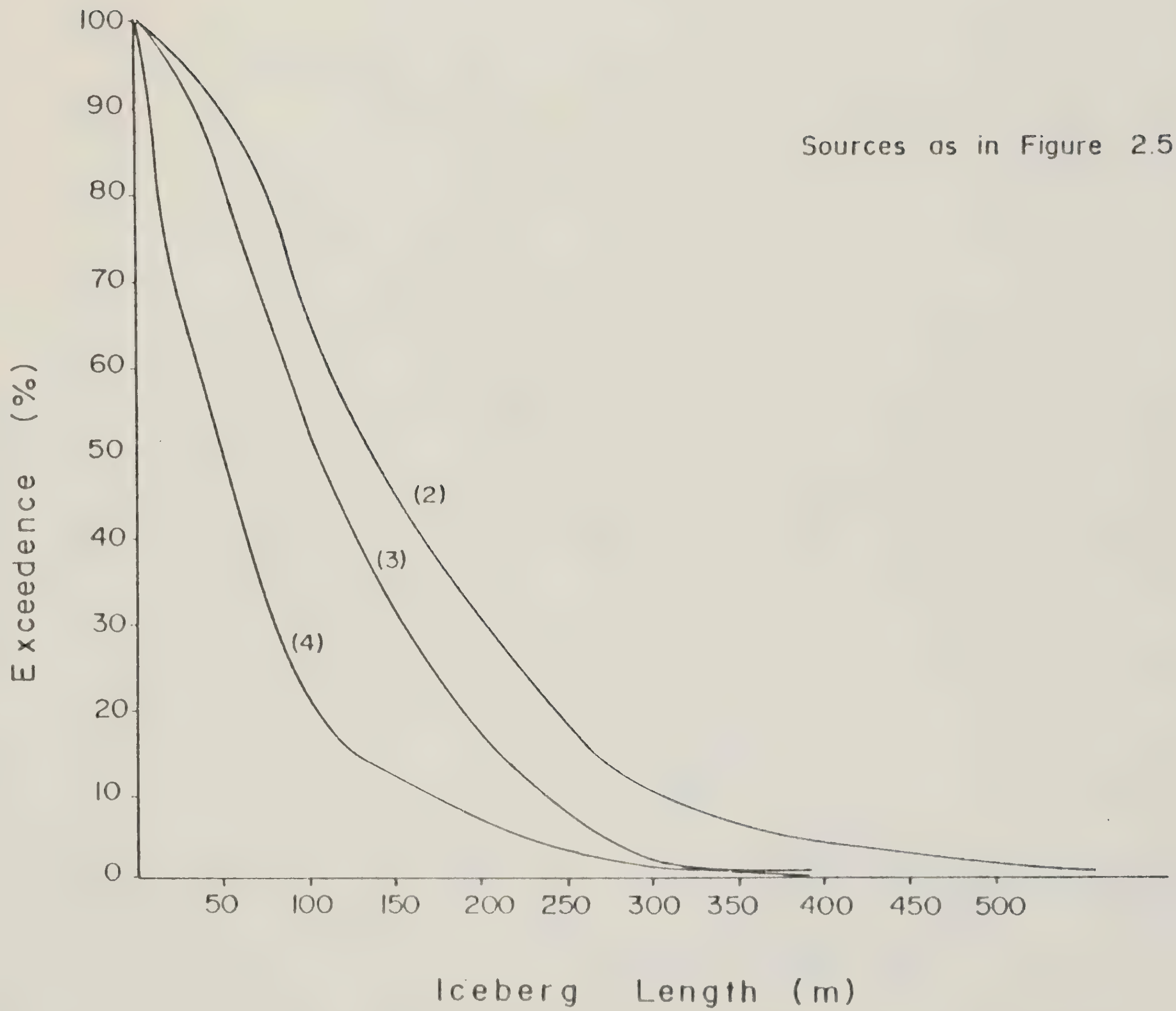

FIGURE 2.6 Percentage exceedence for iceberg length

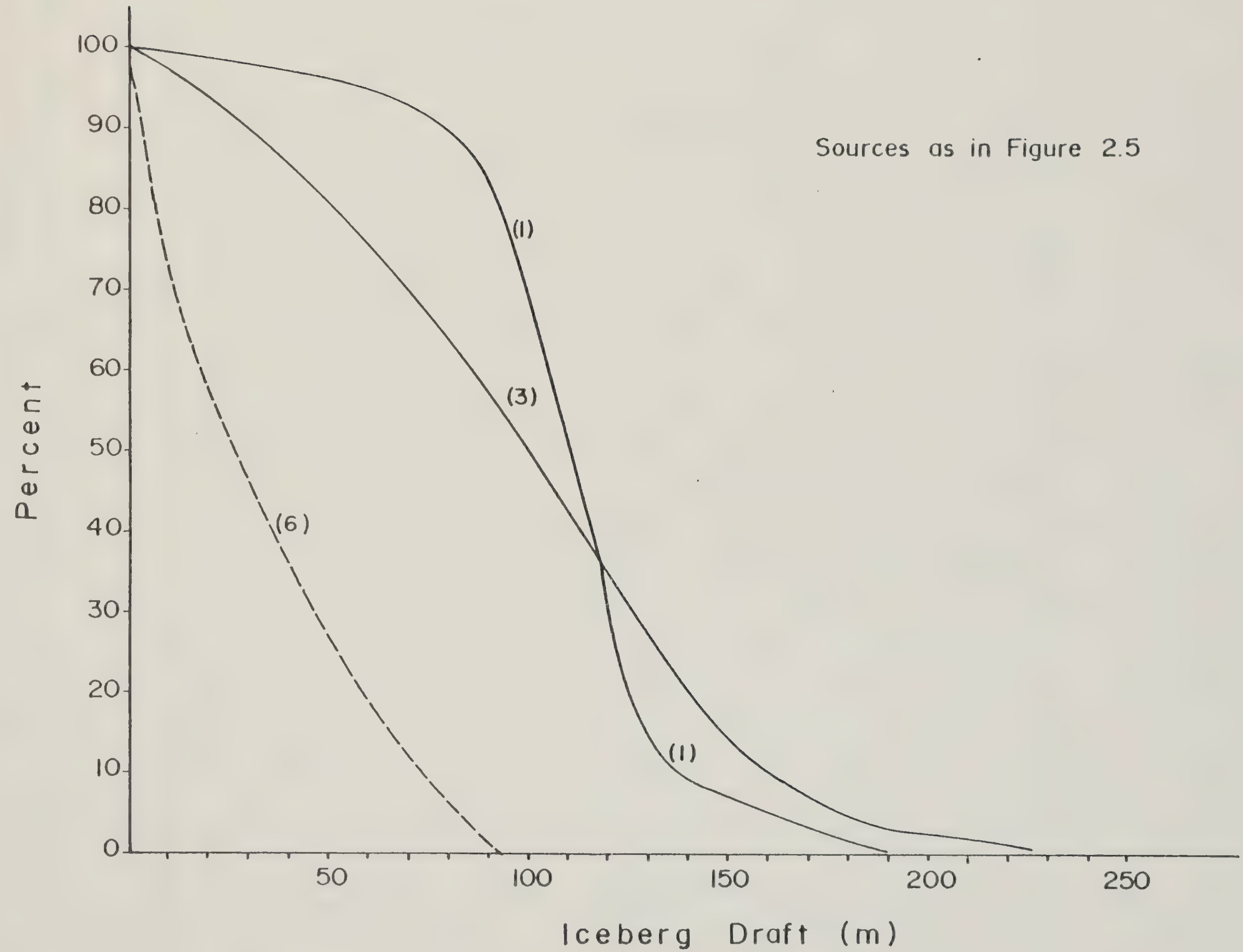

FIGURE 2.7 Percentage exceedence for iceberg draft

Data collected off Saglek, Labrador indicate that from the coastline out to about 16 km the icebergs moved in a southerly direction at speeds of approximately 0.30 to 0.35 ms^{-1} while further offshore the icebergs drifted in a confused manner (Allen, 1972). In most cases these variations are caused by differences in the current regime.

The iceberg speed distribution for a specific site can be calculated either through the analysis of a large data set of iceberg tracks for that site, or by using data sets of wind and current conditions in conjunction with a reliable iceberg drift model to predict the iceberg speed distribution. The first approach would require several years of data covering the entire operating season to define mean conditions, and an even larger data set to adequately define extreme conditions. Since there are few sites in the study area where this type of data is available this approach is not generally applicable. The latter approach requires reliable estimates of wind and current conditions and a proven iceberg drift model. Unfortunately reliable current statistics are available for less sites than iceberg statistics.

The available data on iceberg drift speeds for the study area is summarized in Table 2.2. This table incorporates data from a number of sources which were obtained and analyzed in a variety of ways. Not all of the values presented in this table are directly comparable. For example, data obtained from satellites may represent average drift speeds over a period of 6 to 12 hours, while radar reports from a drill rig may represent drift speeds averaged over periods of less than one hour. This is important since, generally speaking, data averaged over longer time periods will indicate lower maximum speeds. This effect is demonstrated in work by Ball et al. (1981b).

The iceberg drift statistic normally used in design studies is the percent exceedence curve. However, few of the reports listed in Table 2.2 present the data in this format. The statistics generally quoted in these studies are the average speed and the maximum observed speed. Depending on the study, the average drift speed quoted may be the mean, median or modal speed. In some of the cases presented in

Table 2.2, the average speed represents an average speed for one iceberg or a group of icebergs over a period of several days. The maximum drift speeds presented in Table 2.2 generally represent the highest speed recorded from a number of observations.

The data presented in Table 2.2 can be summarized as follows: for sites not in the main current stream, average iceberg drift speeds range from .10 - .25 ms^{-1} while in high current environments average values can approach .50 ms^{-1}. It would appear from the data that maximum drift speeds of 1.5 ms^{-1} are possible in all regions. Although the data base is not sufficient to adequately define low probability events it seems likely that short duration drift speeds of 2.0 ms^{-1} and daily average speeds approaching 1.5 ms^{-1} can occur in high current environments under severe storm conditions. These conclusions are based on several recorded cases of iceberg drift speeds approaching 1.5 ms^{-1} with wind speeds under gale force (Marex, 1977; International Ice Patrol, 1980) and one recorded case of an iceberg averaging 1.25 ms^{-1} over several days under severe storm conditions (International Ice Patrol, 1960). Conclusions regarding drift speeds during severe storm conditions must be speculative since there are few observations under these conditions.

The previous discussion has not presented separate drift speed estimates for different size icebergs. The literature is divided on the question of the effect of iceberg size on drift rate. Very little quantative data presently exist on expected instantaneous speeds of small icebergs such as growlers in waves, and no field data exist at all.

At present design criteria for maximum iceberg drift speeds have only been proposed for the Hibernia development. A maximum iceberg drift speed of 1.0 ms^{-1} is proposed for this area by both the Newfoundland and Labrador Petroleum Directorate and Mobil Oil Canada Ltd. (McIntyre, 1981). Although no probability level is assigned to this value other statistics quoted indicate that it represents a long term maximum.

SOURCE	METHOD	SITE	YEARS	AVERAGE SPEED (m/sec)	MAX SPEED (m/sec)
MAREX (1971)	Ships Radar	Labrador Sea	1971	.17	
" (1972)	"	"	1972	.60*	
MAREX (1973)	"	"	1973	.19	
" (1974)	"	"	1974	.19	1.23
" (1975)	"	"	1975	.15-.27	.94
" (1976)	"	"	1976	.21-.39	1.69
MACLAREN MAREX (1978)	"	"	1978	.17	.86
Memorial University	Shore Radar	"	1972-74	.25	.50
Robe et al. (1979)	RAMS	Baffin Bay/Lab Sea	1978	.10-.20	.80
IVL	RAMS			.18	
MAREX (1972 c)	Ship Sightings	Baffin Bay	1972	.03-.27	
IIP (1959)	Ship Sightings	Grand Banks	1959	1.25*	
IIP (1962)	"	"	1962	.92*	
IIP (1963)	Aircraft Sightings	Labrador Sea	1963	.19	
IIP (1980)	Ship Sightings	Grand Banks	1980		1.30
IIP (1964)	Aircraft Sightings	Labrador Sea	1964	.09-.28	
de Lange Boom et al. 1982	Shore Radar	Baffin Bay	1978	.09-.24	
de Lange Boom et al. 1982	"	Lancaster Sd	1978	.14-.45	

* small sample

TABLE 2.2 Iceberg Drift Speeds

Although no design criteria have been proposed for Labrador a value of 0.80 ms^{-1} is quoted for maximum iceberg drift speed in the Offshore Labrador Initial Environmental Assessment (Petro-Canada, 1982). Both of the above values need to be reassessed in light of the data in Table 2.2.

The previous discussion has focused on the iceberg drift speed, but the direction of drift is an equally important factor. Analysis of data collected at drill sites in the Labrador Sea (Marex Ltd., 1971-77; MacLaren Marex Ltd.) has demonstrated that although there is normally a predominant drift direction, icebergs can drift in all directions. This is an important factor to consider when designing iceberg impact probability models (Trofimenkoff, 1978 and Reddy et al., 1982), however, several of the existing models do not take this into consideration.

2.2.4 Deterioration

Icebergs decay due to melting above and below the waterline, and due to calving. The calving of an iceberg increases the rate of melting due to an increase in the surface area on which melting can occur. Melting of an iceberg in open water generally proceeds most rapidly at the waterline due to the effect of wave action. Icebergs trapped in sea ice deteriorate slowly since they are protected from wave action and are floating in waters with temperatures below their melting point.

The International Ice Patrol has studied the decay of bergs for many years and has developed the deterioration times presented in Table 2.3.

Table 2.3
Deterioration Time (In Days) For Icebergs
(International Ice Patrol, 1976)

Surface Sea Water Temperature	Small Berg Under 15m High Under 66m Long	Medium Berg 16-45m High 61-122m Long	Large Berg Over 46m+ High Over 123m+ Long
$2^{o}C$	9	17	38
$4^{o}C$	6	11	23
$6^{o}C$	4	8	16
$8^{o}C$	3	6	13
$10^{o}C$	3	6	11

For tabular icebergs the height limits are 6m, 6-15m and over 15 m.

2.2.5 Mechanical Properties

The mechanical properties of iceberg ice are directly related to its glacial origin. There are various types of ice in a glacier that can be differentiated by air bubble content, mud or debris content, and by the form, size and crystallographic orientation of the grains. The white appearance of most iceberg ice is due to the scattering of sunlight by air bubbles entrapped in the ice during the transition from snow to ice, while iceberg ice without air bubbles, which has a blue colour, is the result of melt water refreezing in cracks in the glacier.

During the transformation from snow to glacial ice entrapped air is gradually isolated into individual bubbles. These bubbles typically have dimensions of the order of a few tenths of a millimeter and frequencies in the order of a few hundred per cubic centimetre. The bubbles are usually round or ellipsoidal, often with considerable elongation. Due to the large hydrostatic pressure accompanying the

formation of glacial ice, the entrapped air is under compression. This is evident as melting iceberg ice has an effervescent appearance due to the exploding bubbles.

The effect of air bubbles on the mechanical properties of ice has not been experimentally investigated in any comprehensive way. Properties such as Young's Modulus should show declining values with increasing ice porosity. Bubbles may help initiate cracks in ice under high stress or inhibit the propagation of existing cracks by reducing stress concentration at a propagating crack tip. The latter effect probably accounts partly for the apparent higher strength of iceberg ice in uniaxial compression as compared to lower porosity lake ice.

Very little experimental data on the strength of iceberg ice is available in the public literature. In 1982 Ice Engineering Ltd. carried out uniaxial strength tests for the Newfoundland and Labrador Petroleum Directorate (1982a) on iceberg ice obtained from icebergs grounded around the Newfoundland Coast. In conjunction with these tests, samples of ice obtained from a pond near St. John's were also tested. The results of these tests are summarized in Table 2.4. Several significant differences between the mechanical properties of lake ice and iceberg ice are indicated. Young's modulus for lake ice is about 17% higher than the corresponding value for iceberg ice. However, bubbles in the iceberg ice reduce the effective cross-sectional area by 2.3% which in turn could account for a 2.3% reduction in Young's modulus compared to that for bubble free ice.

The mean stress at which the iceberg ice samples failed exceeds the mean failure stress for the lake ice samples by 35%. Lake ice samples underwent less deformation at a given load, but tended to fail at an earlier point on the load curve. Quantitatively this indicates that iceberg ice is more deformable, yet fracture resistant, while the lake ice behaviour is more brittle.

This study concluded that bubbles present in iceberg ice are likely the major factor inhibiting fracture propagation. Microcracks, arising from stress concentrations at crystal grain boundaries,

bubbles or pre-existing internal cracks, can propagate only so long as stress concentration at the leading tip exceeds the strength of the ice. Bubbles, by strongly modifying the stress field in their immediate neighbourhood, could diffuse the concentration of elastic energy at the leading tip and thereby inhibit further development of the crack. Before generalizations regarding the strength of iceberg ice can be stated with certainty, the effects of internal cracks, bubbles and crystal grain structure must all be analysed.

In 1981, Mobil Oil Canada Ltd. (1981f) sampled five different icebergs along the northern tip of Newfoundland near St. Anthony. Twenty-three uniaxial compressive tests at temperatures from $-1.9^{\circ}C$ to $-3.5^{\circ}C$ and a strain rate of 10^{-3} per second gave an average compressive strength of 2.33 megapascals (MPa) with a standard deviation of 1.33 MPa. From borehole jack tests confined compressive strengths at depths of 0.5, 1.0, 1.5 and 2.5 m were respectively, 21.7, 28.0, 30.4, and 30.4 MPa for a step function load (strain rates around 10^{-1} per second).

Other uniaxial compression tests have been carried out by Dr. Arockiasamy and Dr. Swamidas at the Faculty of Engineering, Memorial University (Arockiasamy et al., 1983). Table 2.5 shows the average strengths of iceberg ice they obtained from uniaxial compression tests at various strain rates. The results give a maximum strength of 7.44 MPa at a strain rate of 10^{-3} per second. For a step function load (strain rates around 10^{-1} per second) the strength increases a little above that given for 10^{-2} per second. There is a considerable reduction in strength at $-2^{\circ}C$ compared to that at $-5^{\circ}C$.

TABLE 2.4

Summary Statistics For
Uniaxial Compression Tests
(Newfoundland and Labrador Petroleum Directorate (1982a))

Parameter	Pond ice samples (number of specimens = 13)				Berg ice samples (number of specimens = 11)			
	mean	min.	max.	std. dev.	mean	min.	max.	std. dev.
Data from direct measurements:								
length (mm)	150.8	111	156	11.5	150.2	144	153	2.3
temperature (deg. C)	-4.0	-5.5	-1.5	1.1	-4.2	-6	-3	.8
strain rate (ppt/sec)	1.082	.739	1.815	.276	1.097	.922	1.391	.125
Young's modulus (GPa)	7.121	3.94	9.64	1.476	6.092	4.77	7.23	.675
time to failure (sec)	.575	.43	.91	.131	.836	.72	1.02	.095
stress at failure (MPa)	3.954	2.92	6.72	.963	5.336	4.62	6.72	.731
strain at failure (ppt)	.604	.42	.93	.155	1.015	.69	1.37	.222

TABLE 2.5

AVERAGE STRENGTH VALUES OF ICEBERG ICE
FOR UNIAXIAL COMPRESSIVE STRENGTH
AT VARIOUS STRAIN RATES
(AROCKIASAMY *ET AL.*, 1983)

NO.	ROOM TEMP. (^{o}C)	STRAIN RATE (per sec)	SAMPLE SIZE (N)	AVERAGE STRENGTH (MPa)	STANDARD DEVIATION (MPa)
1	-5	10E-3	7	7.44	1.90
2	-5	10E-2	6	6.94	0.43
3	-5	Step	5	6.97	0.66
4	-2	10E-3	1	5.40	--
5	-2	10E-2	1	3.96	--

TABLE 2.6

AVERAGE STRENGTH VALUES OF ICEBERG ICE FOR SURFACE
INDENTATION STRENGTH TESTS AT VARIOUS STRAIN RATES
(AROCKIASAMY *ET AL.*, 1983)

NO.	ROOM TEMP. (^{o}C)	CONFINED	STRAIN RATE sec^{-1}	NUMBER OF TESTS N	AVERAGE STRENGTH MPa	STANDARD DEVIATION MPa
1	-5	No	10E-3	5	23.26	1.12
2	-5	No	10E-2	5	30.47	1.49
3	-5	No	Step	4	22.74	1.28
4	-5	Yes	10E-3	3	28.43	0.72
5	-5	Yes	10E-2	3	33.97	2.35
6	-5	Yes	Step	3	27.41	1.56

In 1983 NORDCO, under contract with Newfoundland and Labrador Petroleum Directorate (1983c), obtained iceberg ice from a bergy bit grounded in Tor Bay, Newfoundland. Cylinders 0.68 m in diameter and 0.25 m deep were cut from this ice for impact testing. The ice disk was confined along the cylinder axis by an aluminum ring while an indentor weighing 509.8 kg was dropped onto the flat face of the disk. The tests were conducted at impact speeds of 1.7 ms^{-1} and two at 1.0 ms^{-1}. In all cases, radial cracks were formed but these extended to the confining ring only in the high speed tests. Also, ice was ejected from the sample only during the high speed tests. The final shape of the crater appeared to conform to that of the indentor and a low rim of crushed ice was formed around the crater. It was noted that following each test the craters were about half filled with water which formed during impact.

In addition to these results, Table 2.6 gives results of indentation strength tests carried out by Dr. Arockiasamy and Dr. Swamidas at the Faculty of Engineering Memorial University. It was found that the indentation strength increases up to a strain rate of 10^{-2} per second and then decreases.

From the same FENCO work of 1981 carried out for Mobil Oil Canada Ltd. (1981f), fifteen beam bending tests at temperatures from $-1^{o}C$ to $-2^{o}C$ gave an average flexural strength of 1.34 megapascals (MPa), with a standard deviation of 0.14 MPa. Five beam tests at temperatures from $-3.7^{o}C$ to $-4.7^{o}C$ gave an average flexural strength of 1.71 MPa with a standard deviation of 0.06 MPa.

The accuracy of analytical models depends on the quality of data available on iceberg mechanical properties. However, the mechanical properties themselves depend on the nature of the stress during the interaction. This stress behavior must be represented in the mechanical property testing procedures and equipment. Whereas testing the properties of the ice in the field and laboratory can define the nature of the relationships between strength, temperature, air content, etc. large scale testing is required to determine the failure, stress and fracture behavior of ice masses as a whole.

2.3 Exploratory Drilling Operations in the Presences of Icebergs

Exploratory drilling for oil and gas in iceberg infested waters started on June 25, 1971 when the drillship, Typhoon, arrived at a site off the Labrador coast. Only four days later the Typhoon was forced to move off site to avoid an iceberg. Apart from the typhoon and the Zapata Ugland in 1976, all subsequent drilling programs used dynamically-positioned drillships on the Labrador coast. During this period, no serious accidents involving icebergs have been reported. This lack of incidents is due to a number of factors. One of the most important is the ability of dynamically-positioned drillships to quickly move off a site if an iceberg is approaching. A second important factor is the development of iceberg management procedures such as towing and prop-washing. If it were not for these procedures the number of cases where the vessel is forced to move might preclude drilling for economic reasons. The final factor involved relates to the limitations of dynamically-positioned drillships. These vessels cannot operate in sea ice conditions or during severe sea states and, therefore, drilling is restricted to the summer months and the early fall. During this period sea states are such that icebergs are easier to detect and manage.

Offshore drilling on the southern Grand Banks evolved in a different fashion to that off Labrador. In this area fewer icebergs were encountered, weather conditions were more severe and water depths were shallower. Under these conditions anchored semi-submersible drilling platforms were preferred. Drilling on the Grand Banks stopped in the mid 1970's but resumed again in 1979. When drilling resumed, it was further northeast and in a more severe ice environment. During the first three years of resumed drilling on the Grand Banks (1979-81) few problems were experienced, since this period had less severe than normal ice conditions. However, during 1982 and 1983 iceberg conditions on the Grand Banks were more severe, with 1983 being a near record year. During both years problems were experienced with icebergs and during 1983 doubt was expressed regarding the feasibility of winter drilling on the Grand Banks (Newfoundland and

Labrador Petroleum Directorate, 1983b). The main area of concern was that anchored semi-submersible drilling platforms require such a long period of time to safely disconnect. This can be a problem in a storm situation, when the warning period may (on occasion) be very short and management of the iceberg impossible.

Over the years the offshore industry has evolved policies, procedures, and equipment for coping with hazardous ice. More recently, regulatory agencies have developed general guidelines for required equipment and procedures to protect drilling stations from ice hazards, but these generally conform to the industry standards. The Canada Oil and Gas Lands Administration (COGLA) (1983b) document "Physical Environmental Guidelines for Drilling in the Canadian Offshore" is an example. Industry practices are laid down in documents produced by each operator generally referred to as Contingency Plans. The Plans cover the gamut of all possible marine and/or drilling hazards and emergencies including ice encroachment on a site and ice accretion. They specify organization and responsibility, define alarm conditions, and lay down recommended procedures and actions to manage and eliminate the threat. Contingency Plans are required to be submitted by all operators to the regulating authorities as part of the drilling permit application, the Mobil Oil Canada Ltd. document "Mobil Offshore Contingency Plan Volume 77" (1983a) and the Petro-Canada (1983) "Offshore Labrador Contingency Plan" being examples presently on file with COGLA. The Interim Standards for Design construction and operation of Mobile Offshore Drilling Units (MODU's) issued recently by the Canadian Coast Guard (1983) include a list of points (Part XIV) to be addressed in the development of an operations manual.

The development procedures for drilling in the presence of floating ice, particularly icebergs, has resulted in the creation of a unique field of operational support known as Iceberg Management. Ice Management (covering floating ice in general) can be defined as the co-ordinated use of certain equipment, procedures, and personnel with the single objective of minimizing the effects of the presence of ice on drilling station operations. It is considered axiomatic that drill

station management wants to maximize productive operations which can continue only as long as the safety of the station and its personnel and good drilling practice are not compromised by the presence of ice.

The basic elements of an Ice Management system which can be implemented at a local or regional scale are:

- detection capability
- uniform surveillance and measurement procedures
- drift forecasting capability
- capability for controlling iceberg trajectories.

In a local ice management system the key individual is the ice observer who is on duty at all times. This person, who reports to the drilling unit management (marine and drilling), is responsible for detection, surveillance, measurement, and drift prediction of all ice in the vicinity of the drill vessel.

The primary detection tool is marine radar on the drill vessel itself, supplemented with radar and visual observations from other resources, usually patrol/standby boats and sometimes aircraft, which have been placed at the disposal of the observer. Although ice detection is covered in detail elsewhere in this report, it is within context here to state that the commercially available marine radar sets presently in use are not optimized for detection of ice; small pieces of iceberg ice being very difficult targets. These very often look like sea or rain clutter on the radar display and can easily be completely smothered by wave clutter even in moderate sea states. Because of this detection difficulty, coupled with the fact that small pieces of ice can attain much higher speeds than larger icebergs, observers are particularly alert to the possibility that they may be present.

Once detected, ice must be monitored at regular intervals. A key idea here is that of evaluating the level of the threat as the monitoring proceeds. It is this evaluation which determines whether or not collision avoidance procedures are invoked and at what level. The input factors are as follows:

1. The distance of the ice from the station
2. Drift speed and direction
3. Safe stand-down time
4. Collision avoidance constraints (weather, sea state)
5. Forecast drift of the ice
6. Iceberg draft (with respect to wellhead damage potential)

The procedure for assigning level of threat is based on a configuration of concentric alert zones centred on the drilling vessel, a typical example is given in Table 2.7. The zone radii depend on the drift speeds of icebergs as measured or estimated, and the time required to secure operations safely. A key element in this procedure is an effective ice drift prediction capability. Dedicated computers on board have at this time become standard equipment in local ice control. As ice moves into zones of progressively higher alert status specific actions are invoked: the deflection of icebergs away from the site, or preparations to secure the well and move the rig in the case of non-deflectable icebergs or encroaching pack ice.

The aim of the operator's regional management program is to provide advanced warning that ice may enter the local management zone and it is practiced in much the same way as local management described above. There are, however, some important differences. On the local scale most of the required input data is obtained by the observer on the rig for his immediate use. The regional surveillance area is much larger and data on ice movement must be obtained from a large number of sources including government agencies, dedicated operator sponsored surveillance, and sources of opportunity. The data are of non-uniform quality and are available at irregular time intervals. Regional forecasting is usually performed at a shore based facility with the resources to access and evaluate such data. However, key decisions concerning ice avoidance are made by rig management on site using the regional forecast as guidance.

Table 2.7

Typical iceberg alert zones for drilling operations off Labrador

1) Detection:	nominal	50 km
	realistic	30 km
	COGLA	radar range (min. 40 km)
2) Disconnect zone:	1 km	
3) Red Zone:	inner edge = 1 km outer edge = greater of (a) or (b) a) 1 km + 2 x hourly speed of fastest berg b) 1 km + (number of hours to secure well) x hourly speed of fastest berg.	
4) Yellow Zone:	inner edge = outer edge of Red zone outer edge = greater of (a) or (b) a) outer edge of Red zone + 4 x hourly speed of fastest berg b) outer edge of Red zone + (number of hours to terminate operations) x hourly speed of fastest berg.	
5) Green Zone:	inner edge = outer edge of Yellow zone outer edge = limit of radar range.	

An additional regional consideration is the scenario of a densely populated offshore where a relatively large number of drill stations are concentrated in a small area, such as is tending to happen on the eastern Grand Banks. The implication of this trend is that ice avoidance action, such as iceberg towing initiated at one site may cause a threat to another.

Whether or not a local or regional system or a combination of the two is used depends on a number of factors. In the case of a dynamically-positioned drill station, local control will normally be sufficient. Such a station can, in an extreme situation, effect an orderly withdrawal from drilling and associated operations relatively quickly. If a moored drilling station is being used the situation changes dramatically, in that, a considerably longer period of time is required for orderly withdrawal. In the absence of regional data the decision to suspend operations or to prepare for moving off may have to be made very shortly after a potentially troublesome iceberg drifts within local surveillance range.

2.4 Assessment

(i) Icebergs are a significant factor in exploratory drilling operations from the Grand Banks east of Newfoundland northwards. Although icebergs have been observed in the Gulf of St. Lawrence, they are not considered a serious impediment to drilling in the area. Similarly, south of Newfoundland and off Nova Scotia, icebergs are so rare they are unlikely to interrupt drilling operations.

(ii) The iceberg "season" extends from January to July on the Grand Banks, with the maximum flux occuring in April or May. Further north icebergs occur year round. The minimum flux of icebergs in all areas is between October and December.

(iii) The data bases for dimensions, mass, velocity and mechanical properties are generally inadequate for definition of extreme events. The best available data bases are for the Grand Banks south of 48^{o}N and the Labrador continental shelf. However, due to

difficulties in detecting small bergs the data bases for these areas may be biased towards icebergs larger than 1,000 tonnes. Information on mechanical properties of floating ice of glacial origin is inadequate everywhere.

(iv) Operational techniques have been developed that permit exploratory drilling using either dynamically-positioned or anchored platforms in the presence of icebergs. These techniques are generally adequate, but improvements are required in the detection of small pieces of ice, both in terms of increased range and for tracking through sea clutter in the vicinity of the drilling platform. The early detection of icebergs representing a hazard to anchored platforms is essential to their safe operation as lead times for moving such platforms is significantly greater than for the dynamically-positioned systems.

(v) Research on the impact forces between icebergs of various sizes and exploratory drilling platforms, particularly as might occur with severe sea states is in its infancy. Progress is hampered by lack of knowledge of the maximum velocities small pieces of ice might attain, mechanical properties of the ice, and its behaviour in impact situations.

(vi) The presence of isolated growlers can present a hazard to supply vessels, particularly if the vessel is moving at its normal cruising speed on the assumption of ice-free conditions. Ice strengthened vessels are generally used from the Grand Banks north, but the degree of strengthening is unlikely to be sufficient to ensure the safety of the vessel if it is travelling at high speed at the moment of impact. Neither radar nor visual detection of growlers is reliable under the prevailing weather and sea conditions off the east coast.

3.0 SEA ICE

3.1 Introduction

While the technology exists for carrying out exploratory drilling in the presence of some types of sea ice, the added problems imposed by weather conditions and the presence of icebergs has restricted drilling in the study area to periods when pack ice is not present. The only danger from sea ice to the types of drilling currently taking place in the study area is the possibility of pack ice drifting into the drilling area. Current procedures call for operations to be suspended and the drilling unit to move off the site before sea ice moves into the area. However, situations may occur when this would not be possible.

There are two regions of the study area where oil exploration activities are currently taking place in areas where problems from sea ice are likely. On the Grand Banks during the winter months sea ice occasionally extends to the Hibernia area, and off Labrador in the summer the ice edge is normally just north of the drill sites at the start of the season. Throughout the northern part of the study are (Baffin Bay, Lancaster Sound) sea ice is present for most of the year and would pose problems to any future drilling activities. Although sea ice does occassionally cover the Northern Scotian Shelf, it has not been observed at Sable Island. However, sea ice could become a problem further north on the Scotian Shelf.

3.2 General Description of Sea Ice Conditions

3.2.1 Ice Formation, Types and Concentration

In waters with a salinity greater than 24.7 0/00 cooling at the surface results in convective mixing and, therefore, the waters at the surface cannot freeze until the entire layer involved in this mixing has cooled to the freezing point of the water. In most of the study area this mixing is normally confined to a lower salinity surface

layer which is approximately 100 to 200 m thick prior to freeze-up (U.S. Navy Oceanographic Office, 1967).

Once this surface layer has cooled to its freezing point, which is approximately -1.8^{o}C for waters with a salinity of 32 0/00, a slight super-cooling will initiate the formation of fine plates of ice suspended in the water called frazil ice. This frazil ice gradually floats to the surface and forms a soupy layer called grease ice.

If the sea surface is calm at the time of ice formation the grease ice will form a thin elastic crust of ice called nilas. This type of ice formation is most common in sheltered near shore locations and in the open areas between ice floes. However, if the sea is agitated by wave action at the time of ice formation, the grease ice will congeal into circular pieces of ice from 30 cm to 3 m in diameter called pancake ice. As the wave action is decreased by the growing ice sheet these pancakes are incorporated into larger ice floes.

Once an ice sheet has formed the ice is generally classified according to its stage of development. This is closely related to its thickness. Young ice, which is the next stage of development after nilas, ranges from 10 to 30 cm in thickness and can be subdivided into grey ice (10-15 cm thick) and grey-white ice (15-30 cm thick). Sea ice of not more than one winters growth that equals or exceeds 30 cm in thickness is referred to as first-year ice. If the ice has survived at least one summer melt season (to 1st October) it is referred to as old ice, which can be subdivided into second-year ice and multi-year ice.

When sea ice is attached to the land it is referred to as land fast ice, while free floating sea ice is referred to as pack ice. Landfast ice can be formed in-situ or as a result of pack ice freezing to the shore. In most of the study area landfast ice seldom extends more than a few kilometres from the headlands.

In addition to being classified according to type, pack ice is also classified according to concentration or the ratio of the sea

surface it covers. In Canada as elsewhere in the world, ice concentration is expressed as the tenths of the sea surface covered by ice. Mariners often group ice concentrations into classes based on the hinderance to navigation. Examples of this classification are open pack (4/10 to 6/10) and close pack (7/10 to 8/10).

Data on ice types and concentrations in the study area is normally obtained from ship, shore, aerial and satellite observations. Visual identification of new, grey, grey-white and first-year ice from ships, shore stations and aircraft is normally not a problem since these classifications are based on visual appearance. The visual identification of small pieces of old ice which are mixed with first-year ice can be a problem for even experienced observers. The visual estimation of ice concentration is normally possible to within one or two tenths.

If side looking airborne radar (SLAR) is used, the ability to distinguish ice types and concentrations is reduced. When SLAR is used ice is normally classified into four types (new, young, first-year and old), and four levels of concentration (very open, open, close and very close). The ability to classify ice using satellites varies considerably with the sensor used. The NOAA class of satellites, which are widely used for operational ice forecasting, can normally resolve two or three types of ice and three to four levels of concentration.

Markham (1980) provides a detailed analyses of the seasonal variations in ice types and concentrations for: the Gulf of St. Lawrence, the east coast of Newfoundland and the south Labrador coast (Figure 3.1). The overall pattern of ice development is relatively similar in all three areas except for the occurrence of old ice on the Labrador coast.

The old ice found in the study area originates from the channels of northern Baffin Bay, especially Smith Sound, and occasionally from southwest Baffin Bay. In these areas pack ice survives the summer melt and becomes entraped in the newly forming pack ice. The

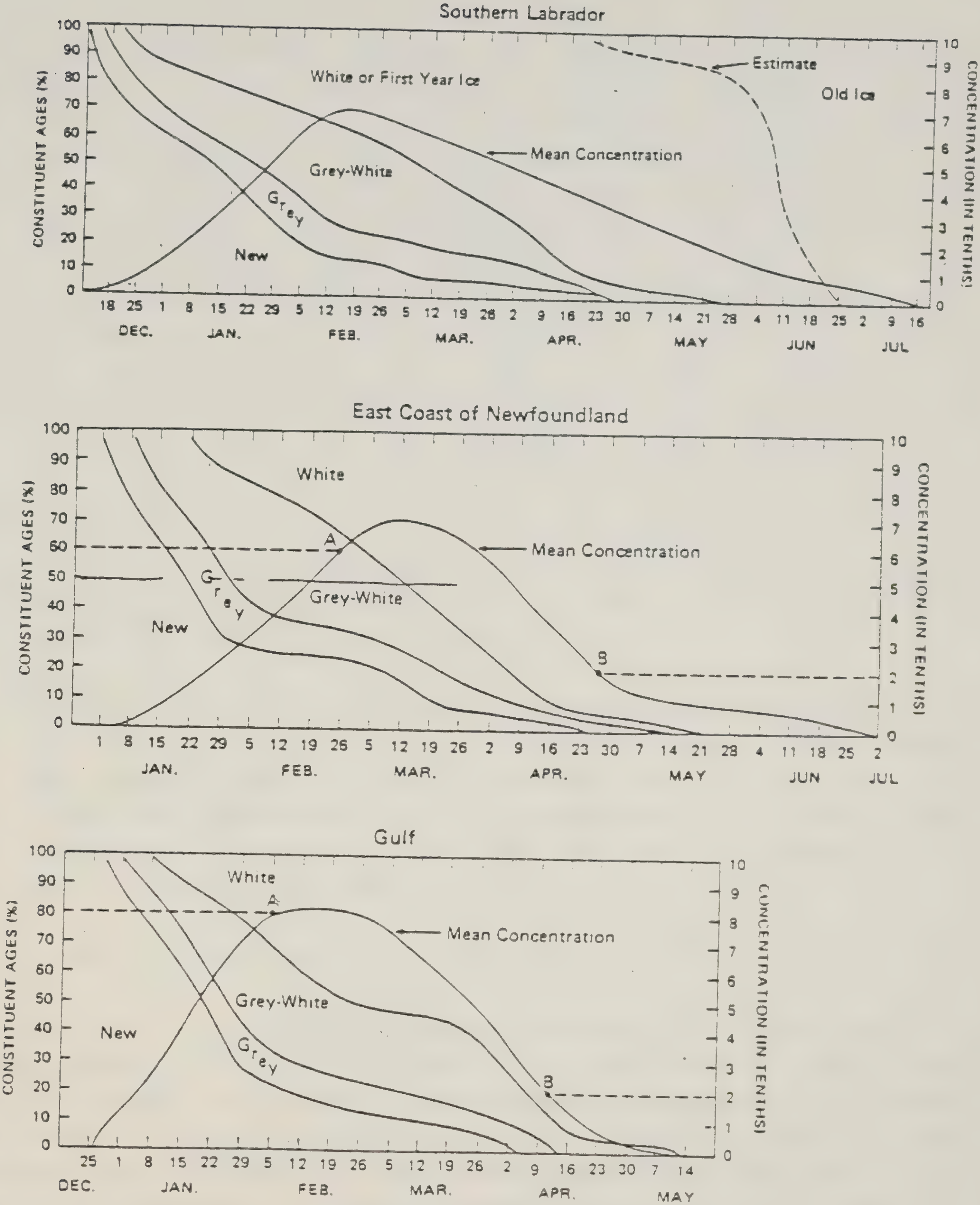

FIGURE 3.1 Seasonal variation of ice types and concentration, (Markham, 1980)

percentage of multi-year ice found in the different regions varies considerably but rarely exceeds one or two tenths outside the source areas. The one exception is along the Labrador coast during breakup when much of the thinner ice melts leaving the multi-year ice. At this time multi-year ice can be the predominant ice type in the strips of remaining pack. While Markham's diagrams (Figure 3.1) do not indicate the presence of multi-year ice on the Grand Banks, the flight charts produced by the Atmospheric Environment Service of Canada (AES) have occasionally noted a trace of old ice in this area late in the season. Based on average drift rates multi-year ice from northern Baffin Bay would not be expected to reach the Grand Banks until late in the season (April). However, during years when there is old ice left in southwest Baffin Bay it reach the Grand Banks as early as February. The available data indicates that the presence of multi-year ice on the Grand Banks is rare, but due to its greater thickness and strength, any old ice that does reach the Grand Banks may reach the southern limits of the pack.

Based on the previous analysis it is clear that the typical sea ice conditions encountered at the start of the summer drilling season on the Labrador coast are low concentrations of first-year and multi-year ice. The typical conditions encountered on the Grand Banks are a mixture of young and first-year ice with the possibility of encountering isolated old floes.

3.2.2 Ice Distribution

Sea ice in the study area normally reaches its minimum extent by mid-September. At this time sea ice is restricted to the extreme northern section of Baffin Bay, the channels of the arctic archipelago and occasionally the southwestern section of Baffin Bay. In late September new ice begins to form in Northern Baffin Bay and the ice edge starts advancing southward (Figure 3.2). By late December the Labrador coast is completely enclosed by ice, and ice is starting to form in the southern Gulf of St. Lawrence. By mid-March the sea ice has reached its maximum extent and completely covers the Gulf of St. Lawrence and much of the Northern Grand Banks. The ice starts to

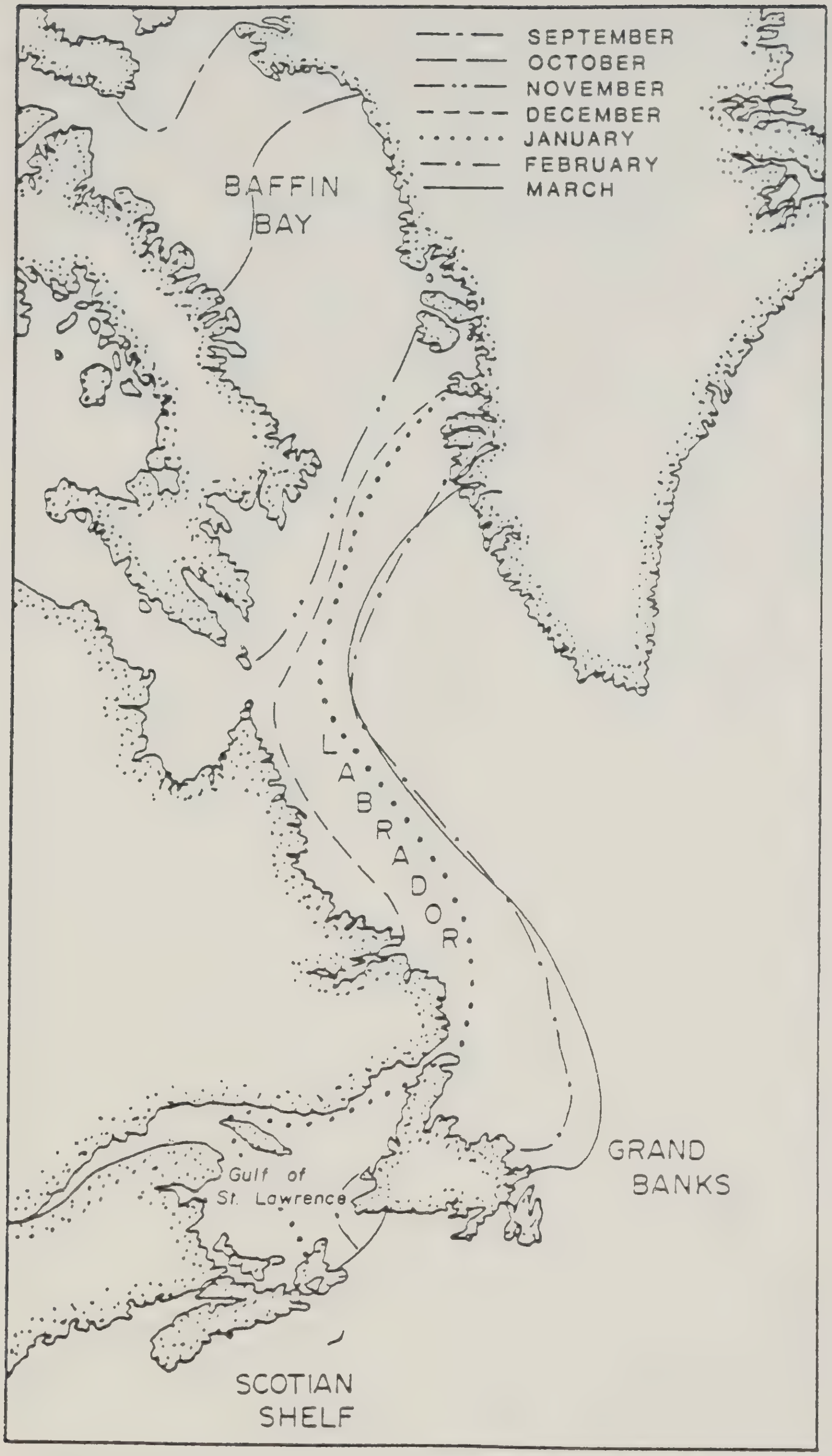

FIGURE 3.2 Advance of sea ice from September to March (Compiled From Sowden and Geddes (1980) and Meserve (1974))

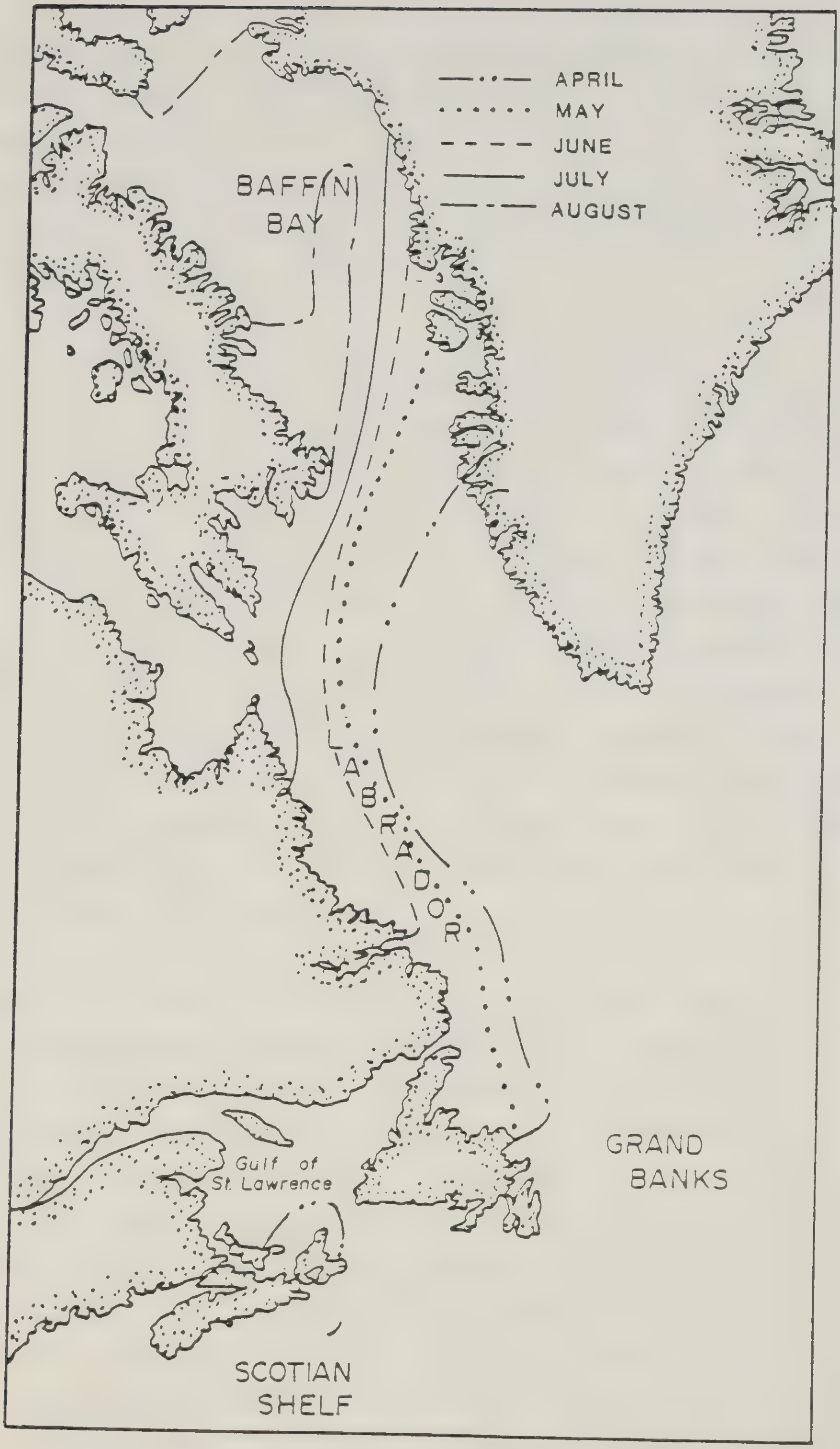

FIGURE 3.3 Retreat of sea ice from April to August (Compiled From Sowden and Geddes (1980) and Meserve (1974))

retreat in April (Figure 3.3) and by May the Gulf of St. Lawrence and the Northern Grand Banks are normally clear. The Labrador coast clears of ice during June and July, while at the same time, areas of open waters in northern Baffin Bay start to expand southward. By mid-August the pack ice has retreated to the extreme northern and southwestern areas of Baffin Bay.

The previous discussion has outlined the normal patterns of ice distribution in the study area. However there can be wide variations in the timing and extent of ice coverage. In most of the study area the timing of the ice advance or retreat can vary by approximately plus or minus one month. The variation in the annual extent of the ice cover is demonstrated by Figure 3.4 which indicates that while much of the Grand Banks is ice free during a normal winter it can be totally ice covered during a severe ice year. Figure 3.4 also indicates that Sable Island is near the extreme limits of sea ice. Ice has come close to the island (within 40 km) on several occasions. The potential for sea ice reaching Sable Island should be investigated further since the jack-up rigs used in this area are limited in their ability to quickly move off site.

The data base for sea ice distribution is more complete than for any other ice parameters. Observations of the position of the ice edge have been collected since the 1800's and in 1889 Robinson compiled a description of sea ice conditions for Newfoundland waters. Prior to the Second World War ship and shore reports were the only source of data but after the war, aerial reconnaissance became the principal source of data. Aerial ice reconnaissance in the study area is currently carried out by the Ice Branch of the Atmospheric Environment Service of Canada (AES) using two Electra aircraft. The introduction of satellite imagery in the mid-1960's increased the frequency of coverage, but did not eliminate the requirement for aerial reconnaissance since the satellite imagery generally used has a much lower resolution and is restricted by cloud cover. The introduction of Side Looking Airborne Radar (SLAR) on one of the AES aircraft in 1980 increased the frequency of coverage for many areas by reducing the dependence on good observing weather. The service should

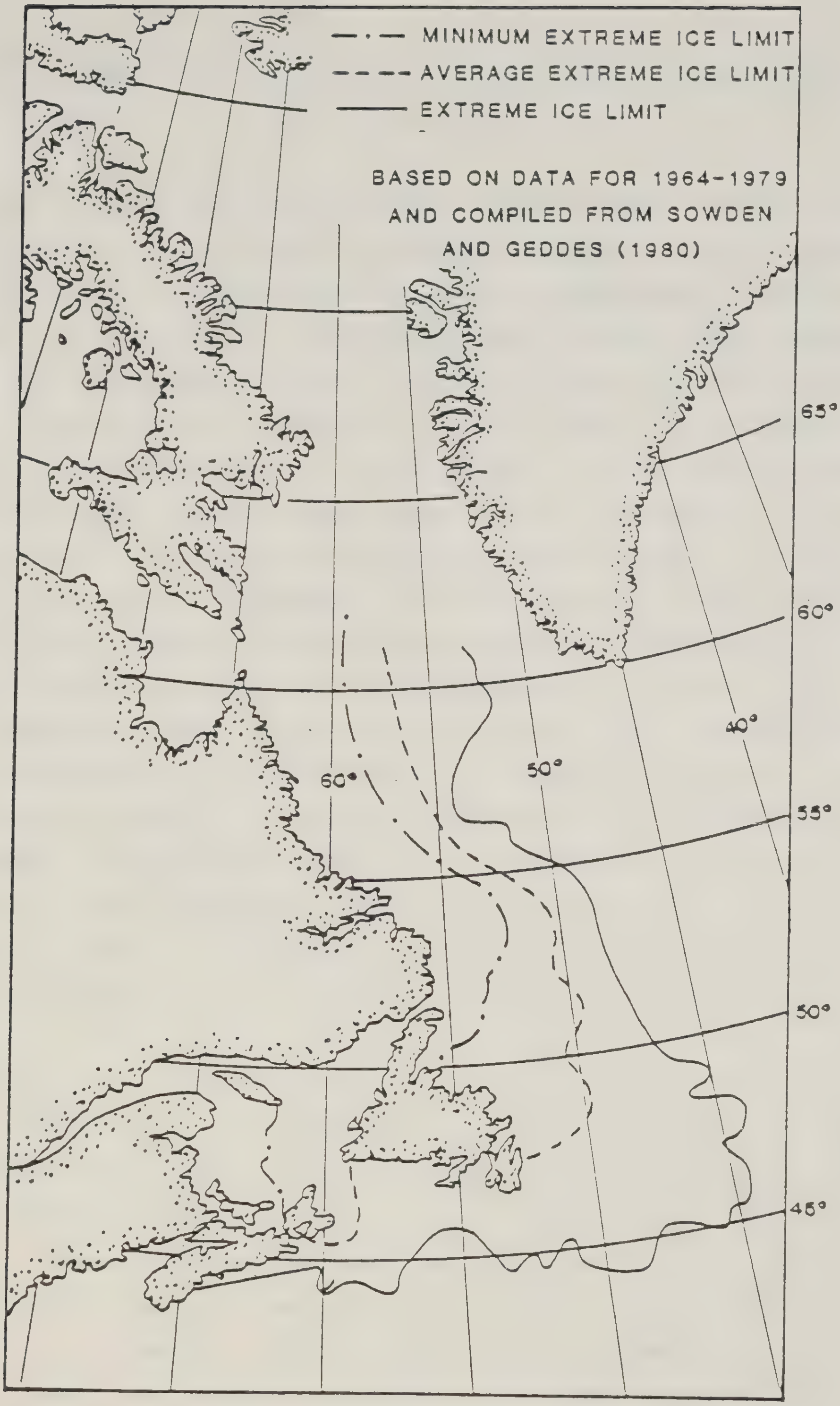

FIGURE 3.4 Extreme sea ice limits

be further improved with the introduction of SLAR aboard the second AES aircraft this year.

The normal AES operating procedures are to have one of the ice reconnaissance aircraft stationed at Gander, Newfoundland during the winter and spring and the other stationed at Summerside, P.E.I. The aircraft stationed in Gander is responsible for providing coverage of the Grand Banks and Labrador coast and the other aircraft provides coverage of the Gulf of St. Lawrence. The AES ice service has a mandate to provide ice information to shipping off the east coast and service to the oil industries is only one of its concerns. Given the large area covered by the aircraft operating from Gander, coverage of drilling sites is limited. Coverage of the Hibernia area during the winter and the Labrador coast during the spring is normally once every two to four days but this can vary considerably. In both of these areas the oil industry has developed its own ice reconnaissance programs which supplement the AES flights. These industry flights rely on visual observations of ice conditions and are normally carried out from twin engine fixed wing aircraft. In both of these areas the industry flights are more frequent than the AES flights during certain times of the year. The oil industry carries out its own analysis of flight data and the results are generally not available to AES.

The reliability of the ice distribution data base varies considerably. Data from the pre-aerial reconnaissance period (approximately 1948) is generally not suitable for site specific analyses. The reliability of the more recent data also varies considerably, with areas where drilling is currently taking place near an ice edge generally being the most reliable. Coverage by SLAR equipped AES aircraft normally takes place several times per week and this is supplemented by visual flights carried out by the oil industry. Unfortunately during the periods when coverage is most urgently required, such as during storm conditions, visual flights by the industries aircraft may not be possible. During these periods the AES SLAR equiped aircraft may be able to provide additional coverage, as was done on the Grand Banks in 1983, but this aircraft is not

dedicated to this task. No studies of aerial observing conditions during periods of ice advance could be identified.

3.2.3 The Advance and Retreat

The pattern of ice distribution is controlled by the advance and retreat of the ice edge. The rate of advance of the ice edge is the most important consideration for drilling since it determines the amount of lead time available to move the drilling unit off the site. The factors controlling the position of the ice edge are: ice formation, ice melt and ice drift.

The formation of new ice ahead of an ice sheet can result in rapid advances of the ice edge under some conditions. However, the ice formed in this way presents few problems for navigation and is quickly broken up by wave action. The melting of pack ice, while not normally considered as a problem, can lead to an increase in the relative proportion of heavy ice. This process often occurs when an ice edge is retreating due to wave action with subsequent packing of the heavier ice by wind action. Under these conditions the ice edge consists of a line of heavy floes which have survived while the thinner ice which once surrounded them has melted. This heavy ice will then form the leading edge of the pack if the ice should advance again.

Ice drift is the most important factor responsible for advances of the ice edge in the study area. The forces that control sea ice drift are wind stress, water stress, the coriolis effect, the internal ice stress, which is a function of the interaction between floes, and the force due to the tilting of the sea surface. In its simplest form, the drift of open pack can be approximated by the resultant vector of the surface current and two to four percent of the wind speed. In fact the response of ice to both wind and ocean currents depends upon a number of factors including the roughness of the ice, the stability of the atmosphere and the stratification of the oceans. When close pack is considered, the internal ice stress becomes especially important.

Analysis of sea ice drift speeds off Labrador (Petro-Canada, 1982) indicates that the maximum observed drift speed was 1.6 kts with mean speeds ranging from 0.34 to 0.64 kts. It should be noted that many of these speeds were observed in pack ice situations. Isolated floes could be expected to travel considerably faster. There are few measurements of sea ice drift speeds on the Grand Banks. However, a study carried out for Mobil Oil Canada Ltd. (1980) by NORDCO Ltd. found a maximum rate of advance of the ice edge towards the Hibernia site of 150 nmi per week (average speed 0.86 kts). Rapid advances of the pack ice on the Grand Banks normally occur in the area of the Labrador current during periods of strong north or northwest winds behind a low pressure system. During a case such as this in March 1973, sea ice advanced south through the Avalon Channel at a rate in excess of 27 nmi/day (AES Ice Charts). No evaluation of sea ice drift speeds on the Scotian Shelf could be found.

Data on the movement of the ice edge can be obtained by monitoring the drift of individual ice floes or by monitoring the position of the ice edge over a number of days. While the first method gives reliable estimates of the ice drift within the pack, it is often difficult to monitor the drift of ice floes near the ice edge. In addition the movement of an individual flow may not be representative of the movement of the ice edge. The second method requires frequent reliable coverage of the ice edge. While this later method has been used to monitor changes in the ice edge (LeBlond, 1982; Mobil Oil Canada Ltd., 1980), no studies could be identified which use this method to analysis rapid advances of the ice edge.

3.2.4 Thickness, Floe Size and Surface Features

The thickness of sea ice is determined by its rate of growth and by deformation due to ridging and rafting. The rate of growth of sea ice is determined by: the air temperature, the heat flow from the water column, the thickness of the ice, and the snow cover on the ice. In the most of the study area, with the exception of some areas in Baffin Bay, first-year ice normally will not exceed 2 m in thickness due to normal growth. In the pack ice environment ridging and rafting

play an important role in the growth of sea ice. Rafting, where one ice sheet over rides another, is mainly a factor in thinner ice. Ridging, where a line of broken ice is forced up by contact between two pieces of ice, can occur in even the thickest ice although the thinner ice is normally incorporated into the ridge. After ridge formation the ice blocks involved can become frozen together which results in the formation of thicker floes.

Analysis of ice thickness measurements in the Labrador Sea (Table 3.1) indicates that the mean first-year ice thickness in this area during the winter months ranges from 0.5 to 3 m, with the maximum thickness near 5 m. There are few measurements of multi-year floes in the Labrador Sea but the available data indicates that thicknesses in excess of 14 m are possible. While some melting can be expected during the spring, the winter ice thickness values can be considered as representative of conditions just prior to breakup. Unfortunately there are few ice thickness measurements during breakup due to the problems associated with working on the ice at that time.

The thickness of ice found on the Grand Banks is primarily determined by conditions that exist further north. Based on temperatures at St. John's, only a very thin ice cover would form locally on the Grand Banks. There are only a few ice thickness observations from the Grand Banks and some of these were collected during mild ice years. The available data is not sufficient to reliably estimate the mean or extreme sea ice thickness.

The flow size distribution within the study area varies regionally, seasonally, and with the distance from the ice edge. The largest ice floes are found in Baffin Bay and off the Labrador coast during the winter months. These floes can reach tens of kilometers in diameter and are composed of smaller floes that have frozen together. Since these floes would be quickly broken up by wave action they are normally found well inside the ice edge. Near the edge of the Labrador pack in winter there is normally a zone from 5-10 km wide with small broken and deformed floes having diameters from 10-20 m. These floes have been broken by the action of wind waves and swell.

TABLE 3.1

Summary of first-year ice thickness measurements in Labrador Sea. All measurements were obtained by ice coring .

Year	Month	Area	Mean (m)	Range (m)	No. of samples	Source	Comments
1971	March	Southern Labrador	-	0.3 - 1.2 non-ridged	-	Nolte & Trethart (1972)	Area was heavily ridged and rafted with ridges estimated up to 7 m thick
1972	April	Off Cartwright	1.37+	0.46-2.56+	40	Bradford (1979)	Heavy ridging, many sails >3m. + sign indicates hole not completely drill through.
1976	February	Off Nain	0.56	0.28-1.22	9	FENCO (1976)	
	March	Between Hopedale and Cartwright	2.83	0.73-7.62	42	FENCO (1976)	
	April	Between Nain and Hopedale	2.97	0.79-7.87	12	FENCO (1976)	
1977	February	Off Saglek	1.60	0.7 - 3	20	NORDCO/C-CORE (1977)	
		Off Hopedale	1.22	0.17-3.2	13		
1978	January	Off Nain	1.09	0.13-2.87	32	FENCO (1978)	
		Off Hopedale	0.76+	0.21-1.73+	43	FENCO (1978)	
		Off Cartwright	0.92	0.51-1.37	15	FENCO (1978)	
1978	February	Off Nain	1.91	0.94-4.48	32	FENCO (1978)	
		Off Hopedale	2.82	0.79-4.57	44	FENCO (1978)	
		Off Cartwright	1.76+	6.70-4.57+	14	FENCO (1978)	
1979	January	Off Hopedale	0.94	0.21-2.40	16	FENCO (1979)	
1982	March	Near $55^{O}N$ $56^{O}W$	2.59	0.68-4.50	19	Newfoundland Department of Development (1982)	

There are few measurements of floe size off Labrador during breakup but conditions are likely to be more similar to the ice edge zone in winter.

Measurements of floe size on the Grand Banks indicate that within 100 km of the ice edge the majority of ice floes will be less than 30 m in diameter. Due to the limited data available it is impossible to derive estimates of the maximum floe size for the Grand Banks.

The occurrence of old floes on the Grand Banks is rare and, therefore, estimates of floe size are unreliable. However, a possible old floe was observed on the Grand Banks in early March 1971 which had estimated dimensions of 10 m by 24 m.

As was stated earlier in this section, the deformation of ice by ridging and rafting can greatly increase its thickness. Ridge formation occurs in almost all pack ice environments but, is most common in regions with high concentrations of ice with varying thicknesses. In these areas there is a greater probability of interaction between floes which result in ridge formation. In addition, ridges are more likely to retain their identity after the pressure decreases if they are formed in a cold environment with little wave action. For these reasons there are few ridges formed in areas such as the Grand Banks where there are low concentrations of ice, relatively warm temperatures and a considerable amount of wave action.

Statistics derived from analysis of laser profilometer data collected by AES off Labrador (NORDCO, 1977) indicate that the largest ridge observed had a sail height of 3 m. Using sail to keel ratios of from 3:1 to 5:1 would give a maximum ridge thickness of from 12 to 18 m. Based on the same stastistics, a typical ridge in this area has a height of approximately 1.5 m and a total thickness of from 6 to 9 m.

There are few measurements of ridge height on the Grand Banks. In March 1979 (a light ice year), an AES ice reconnaissance flight

measured ridge heights on the Grand Banks using laser profilometry (Mobil Oil Canada, Ltd. 1980). Only four ridges were found, two approximately 0.8 m above water and two approximately 0.6 m above water. A photograph of an ice floe on the Grand Banks at 45°50'N 49°20'W taken on April 9, 1921 (Smith, 1931), shows a a ridge with a sail height of approximately 1-2 m. In March 1972 a large first-year floe was observed near 50°55'N, 51°25'W that had ridges that were estimated at from 3-4.5 m in height (Convey, 1972). Based on the available data it is impossible to estimate the maximum ridge thickness on the Grand Banks. However, ridges with thickness of 5 m seem likely.

3.2.5 Mechanical Properties

To date a great deal of world class research has been done in Canada on carefully prepared laboratory ice. This ice has been formed in such a way as to avoid any effect structural variation would have on test results. The behaviour of single crystal and uniform polycrystalline ice have consequently come to be well understood. Mechanical properties such as flexural, shear, compressive and tensile strength, stiffness and elastic modulus, and fracture toughness have all been investigated in the laboratory. This testing has revealed that these properties vary with: temperature, salinity (i.e., brine volume), density, ice grain size and grain orientation.

After ice testing moved from the laboratory to the field, researchers found that the results obtained varied considerably with the size of the sample tested. Primarily, this is because as the size of the field ice sample tested increases, the number of naturally occurring flows and faults in the ice increases, and thus failure may occur at lower stress levels. It is this that laboratory tests are unable to quantify. To the design engineer the results of laboratory tests are not directly useful in quantifying the load conditions he may expect his structure to encounter in an ice-structure interaction. It has also been found that ice properties change significantly within minutes of removing a sample from its field environment, primarily due to brine drainage and temperature changes. There is therefore a need

for full scale in-situ testing of ice. It is only with the results of such tests that the design engineer may proceed with confidence that he has proper quantitative information about the ice environment his structure must be designed for.

The strength of sea ice has been found to depend primarily upon the temperature, the rate of stress application and the entrapped brine volume or salinity. Low brine volumes and temperatures correspond to the strongest ice in all failure modes. Cold multi-year ice which usually has a low brine volume because of drainage and refreezing can be expected to have higher failure strengths than first year ice at the same temperature.

Variation of strength with stress rate is complex and seems to depend on the failure mode. In tension the failure strength increases and then decreases to become independent of stress rate above values of 50 kPa per second. In bending the strength decreases and then increases with stress rate. The value at which the change takes place increases with temperature and does not appear to exceed 100 kPa per second. In compression, the failure strength varies inversely as the stress rate up to values of about 800 kPa per second.

In general, confined compressive strength is higher than the unconfined compressive strength. Shear strength is lower than the compressive strength but higher than both the tensile and flexural strengths. However, comparing ice strength data from various research programs is difficult due to the properties discussed above and the variability in measurement techniques used by different researchers.

With respect to sea ice data for Eastern Canada, most of the measurements have been made in the Labrador Sea. Very few measurements have been made of the properties of sea ice south of latitude 52^{o}N, roughly the latitude of the entrance to the Strait of Belle Isle.

For Labrador sea ice, there are three major sources of field strength data: Petro Canada (a review document 1982), Butkovich (1956)

and Nolte and Trethart (1972). The results obtained by Butkovitch are from landfast ice near Hopedale, while the other measurements were made from ice within the Labrador pack. Table 3.2 summarizes much of the existing data for Labrador. The confined compressive (borehole jack) strengths ranges from 8-12 MPa, unconfined compressive strengths from 4-8 MPa, tensile and flexural strength from 0.5-01.0 MPa with shear strength of 2.0 MPa.

In 1981 FENCO, working under contract to Mobil Oil Canada Ltd., (1981i) measured the properties of sea ice along the southern Labrador coast. This was a light sea ice year with no sea ice in the Hibernia area. From 22 samples tested in the field during March 7-10 the average uniaxial compressive strength was 1485 kilopascals (KPa) with a standard deviation of 708 KPa. For 5 samples tested during April 9-14, the average uniaxial compressive strength was 987 KPa with a standard deviation of 203 KPa. From 11 beam bending tests during March 7-10, the flexural strength was 273 KPa with a standard deviation of 133 KPa.

No measurements of sea ice properties in the Grand Banks area have been published. While it would appear that reasonable extrapolations from Labrador data could be made on the basis of the dependence of strength on the brine volume, the large scatter in strength data tends to complicate this approach. The various mechanical properties of Grand Banks ice should be lower than those for more northern ice, but because of the large variations in data, measurements of Grand Banks ice under standard test conditions are required.

Very few measurements of the elastic modulus (E) of eastern Canadian sea ice have been made. Some measurements were made by Butkovich (1956) in conjunction with his ice strength studies near Hopedale, which is approximately mid-way along the coast of Labrador. Butkovich's results for different temperature ranges are shown in Table 3.3. The overall average was 8000 MPa at a temperature of $-10.4^{\circ}C$.

TABLE 3.2

Summary of strength measurements of Labrador Sea first year ice

	Ice Strengths (MPa)				
	MEAN	S.D.	NO. OF OBSER-VATIONS	MAX	MIN
CONFINED COMPRESSIVE STRENGTH					
FENCO 1975	12.0	4.9	-	-	-
FENCO 1976	16.1	5.5	254	-	-
FENCO 1977 - ALL	8.7	3.8	83	-	-
- FEBRUARY	8.8	3.9	-	12.0	0.2
- MARCH	10.2	3.8	-	14.2	0.3
- APRIL	12.5	3.5	-	15.1	3.5
- MAY	7.8	3.5	-	15.5	0.3
FENCO 1978	10.1	3.5	-	20.9	6.0
FENCO 1979	9.4	2.8	2	-	-
UNCONFINED COMPRESSIVE STRENGTH					
FENCO 1975	4.1	-	-	-	-
FENCO 1976	6.8	1.8	-	-	-
FENCO 1977	4.6	1.5	-	-	-
FENCO 1978	8.6	6.2	5	7.1	0.9
Butkovich (1956)	8.2	2.5	58	10.7	2.6
Nolte and Trethart (1972) horiz.	1.3	1.0	82	3.3	0.2
Nolte and Trethart (1972) vert.	1.7	1.3	47	3.3	0.3
FLEXURAL STRENGTH					
Butkovich (1956)	0.8	0.2	39	1.7	0.1
Butkovich (1956) cantilever	0.3	0.1	10	0.4	0.2
TENSILE STRENGTH					
Butkovich (1956)	0.9	0.4	124	2.2	0.3
Nolte and Trethart (1972) horiz.	0.3	0.1	103	0.6	0.1
Nolte and Trethart (1972) vert.	0.3	0.1	101	0.5	0.1
SHEAR STRENGTH					
Butkovich (1956)	1.9	0.7	46	3.4	0.8

TABLE 3.3

Young's Modulus, Hopedale - March, 1956

(Butkovich, 1956)

Temperature Range °C	Mean
-4.0 to -5.5	7570 MPa
-5.6 to.7.1	7900
-14.5 to 18.3	8270

On the basis of dynamic measurements by Weeks and Assur (1967) in the Canadian Arctic, it can be concluded that:

1. E increases almost linearly with decreasing temperature, ranging from 4000 MPa at $-1.0^{\circ}C$ to 6000 MPa at $-5.0^{\circ}C$.

2. E decreases with increasing brine volume, ranging from 7500 to 10,000 MPa for salinity values typical of Labrador Sea ice.

3. E values for cold, low salinity Arctic sea ice do not exceed 10,000 MPa, but do not fall below 7000 MPa even for very high salinity.

3.3 Exploratory Drilling Operations in the Presence of Sea Ice

As was stated earlier in this chapter, exploratory drilling in the study area does not currently take place in sea ice covered waters. The only danger from sea ice would occur if the pack ice was to drift over a drilling site before a unit could be moved. For dynamically positioned drillships and semi-submersible drilling platforms this would only occur if the sea ice remained undetected, or if the unit was unable to abandon the site for some reason.

There seems little likelihood of failing to detect a significant area of pack ice approaching a drilling area. However, isolated floes could remain undetected during storm conditions. Further research is required to define the probability of such an event and the characteristics of the ice which would be involved.

It is not within the scope of this study to define the conditions under which a drilling unit would be unable to move off a site if sea ice were approaching. The effect that such ice would have on operations would depend on the type of rig involved and the environmental conditions at the time. Experience in the Beaufort Sea has indicated that anchored drilling units can remain on station in the presence of sea ice with the assistance of icebreaking supply vessels, if the sea state and ice drift speeds are minimal. No data

is available to define what these limits are. Dynamically-positioned vessels would likely experience considerable difficulty remaining on station if pack ice was in the area. The main difficulty in this case would be broken ice being drawn into the thrusters. If dynamically positioned drilling units are considered for use in an area where new ice formation is occuring, for example the Grand Banks in winter or the late fall off Labrador, the effect of injesting frazzle ice into the thrusters should be investigated. This ice can occur at depth, and may result in ice build up in intakes.

The possibility of sea ice reaching the jack-up units situated off Sable Island was noted earlier. While the probability of such an event occuring is likely very low, no evaluation of the risk could be identified.

3.4 Assessment

(i) The most significant effect of sea ice on current drilling activity within the study area is to limit the drilling season.

(ii) Current operating procedures call for the drilling unit to move off location if sea ice is threatening.

(iii) Drilling is currently taking place in two areas where sea ice is likely to be a problem. These areas are the Grand Banks in winter and off the Labrador coast in the early summer.

(iv) The two situations identified where the danger from sea ice would be the greatest are: (a) collision with an isolated floe drifting ahead of the main pack during a storm situation and (b) sea ice drifting into the drilling area in a situation when the unit could not move off site.

(v) There is insufficient data available to define the risks associated with (iv).

(vi) The data base for many sea ice parameters is not sufficient to define the effects of an impact.

4.0 ICING

4.1 Introduction

Icing has a number of direct and indirect effects on drilling operations including:

(a) reducing the stability of drilling platforms and support vessels;

(b) restricting the operation of fixed wing aircraft and helicopters;

(c) increasing the danger of accidents as a result of slippery decks; and,

(d) interfering with the operation of safety equipment such as liferafts, radios and radar.

The effects of icing are generally compounded since icing conditions normally occur during periods of severe wind and sea state conditions.

4.2 Summary of Information Available

Icing can originate from either marine or atmospheric sources. The marine sources of ice accretion are freezing sea spray and flooding by waves which can result in ice formation on deck areas. The atmospheric sources of icing are: freezing precipitation (rain and drizzle), (rime icing in cloud and fog) and wet snow which freezes on contact with a surface. Snow which collects on deck areas of vessels and drilling platforms, but does not freeze, will also effect operations. Combinations of icing events occuring either simultaneously or sequentially must also be considered.

4.2.1 Icing From Marine Sources

Freezing spray is the most common source of marine icing. Flooding of deck areas by waves can result in ice formation but is normally not a problem (Minsk, 1977). Sea spray icing occurs when spray droplets

are cooled below the freezing point of sea water (normally $-1.8^{\circ}C$) without freezing. When these supercooled droplets impact with a cold structure or when cold spray hits a very cold structure, freezing may occur. A more complete discussion of the freezing and deposition of sea spray droplets can be found in Stallabrass, (1980).

The rate of sea spray icing is controlled by environmental conditions and factors related to the nature of the vessel under consideration. Since sea spray icing is normally not a significant factor at heights greater than 15 m above the wave crest it is normally not a source of aircraft icing.

The two environmental factors which have the most significant impact on the rate of sea spray icing are wind speed and air temperature. The wind, and the waves it generates, determines the amount of spray produced and the length of time the droplets remain airborne. Shellard (1974) points out that a small vessel will start to generate spray at wind speeds of 17-21 kts and the same vessel moving against the sea in winds of 22-27 kts will be showered in spray. However, spray blown from wave tops is not a major factor until winds of 41-47 kts are reached. This is significant since anchored drilling platforms will not generate as much spray from impact with the waves as vessels moving into the seas and therefore spray blown from the wave tops will be a more significant source of icing.

Air temperature is the second major factor which influences the rate of sea spray icing. As the spray droplets are blown through air with temperatures below the freezing point of sea water they become supercooled and many freeze on contact with a surface. Icing can occur at air temperatures above $-2^{\circ}C$ but is normally not a problem until air temperatures reach $-3^{\circ}C$ or lower. Some early research indicated that sea spray icing would not occur at air temperatures below $-18^{\circ}C$, however, icing has been observed at temperatures as low as $-26^{\circ}C$ (Minsk, 1977). The rate of cooling of the spray droplets in the air is influenced to some degree by the initial temperature of the water, however, icing has been reported with water temperatures as high as $+6^{\circ}C$ (Shellard, 1974).

Apart from wind speed, wave height, air temperature and sea surface temperature, there are a number of other factors which have a less important influence on the rate of icing. Salinity can influence on the rate of icing, but under the normal range of salinities found in the marine areas of Eastern Canada it is not a significent factor. Relative humidity can also influence the rate of icing (Wise and Comiskey, 1980) but its effect is also normally not significant in the study area.

Observations of sea spray icing are included as part of the standard marine meteorological reports sent in by ships and drilling rigs off the east coast of Canada. However, the limited amount of data included in these reports, the variability in observing procedures and the fact that many ships fail to report icing conditions make this data practically useless. The National Research Council of Canada attempted to collect a better data set during the years 1968 to 1979 (Stallabrass, 1980). However, this data is limited in its spatial coverage and is based heavily towards reports from fishing vessels. The spatial distribution of icing observations collected by this program (Figure 4.1) may reflect the pattern of fishing activity in the study area rather than the frequency of icing conditions.

To overcome the limited data base of icing observations a number of methods have been developed for predicting the severity of icing conditions using environmental data. These methods can be divided into those which are based primarily on a theoretical approach and those which are based on an empirical approach.

Two of the most widely used empirical methods are the icing diagrams produced by Sawada (1962) and Mertins (1968). Both of these diagrams are based on observations of sea spray icing on vessels. The diagram produced by Sawada, and modified somewhat for use in Canadian weather forecasting offices (Maxwell, 1982), uses air temperature and wind speed to predict the severity of icing in four classes (Figure

FIGURE 4.1 Locations of reported ship icings off Eastern Canada (Stallabrass, 1980)

4.2). The diagram produced by Mertins (Figure 4.3) is based on approximately 400 observations of icing on German fishing trawlers in North Atlantic waters. This diagram uses air temperature, wind speed and sea surface temperature to predict the rate of icing in centimeters per 24 hours. Mertins diagram is perhaps the most widely used method for predicting icing rates. The method is used by a number of national weather forecasting services and has been adapted for use in areas with different environmental conditions (Wise and Comiskey, 1980). The only general criticism of Mertins method is that it tends to underestimate the rate of icing on smaller fishing vessels (George, 1975; Stallabrass, 1980).

A number of theoretical methods are available for calculating icing rate. The Soviet models (Kacharin, et al., 1974; Borisenkov and Pchelko, 1975) conflict to such a large degree with established emphirical methods, such as Mertin's, that they are suspect. In addition "many of these methods take a rather complex approach which seems to be rather unjustified in view of the uncertainties in measuring or estimating the various atmospheric and ocean parameters as well as representing the rate of icing for the vessel" (Stallabrass, 1980). A simplified theoretical approach presented by Stallabrass (1980) gives results which are in closer agreement with the emphirical methods.

The relationship between environmental factors and icing rate is demonstrated in Figure 4.4. This figure presents a comparison of the icing rates predicted by the Stallabrass (1980) theoretical model and Mertins graphs for a standard set of conditions. Although Mertins model gives slightly lower values, it is apparent that the two methods are in general agreement. The lower values for Mertins model are not surprising since the Stallabrass model was calibrated using data from smaller Canadian fishing trawlers which tend to accumulate more ice.

The potential icing season in the study area can be easily identified by applying any of the icing models to environmental data for the offshore. Figure 4.5 indicates the potential sea spray icing season in each of the study regions. Periods with sea ice coverage are

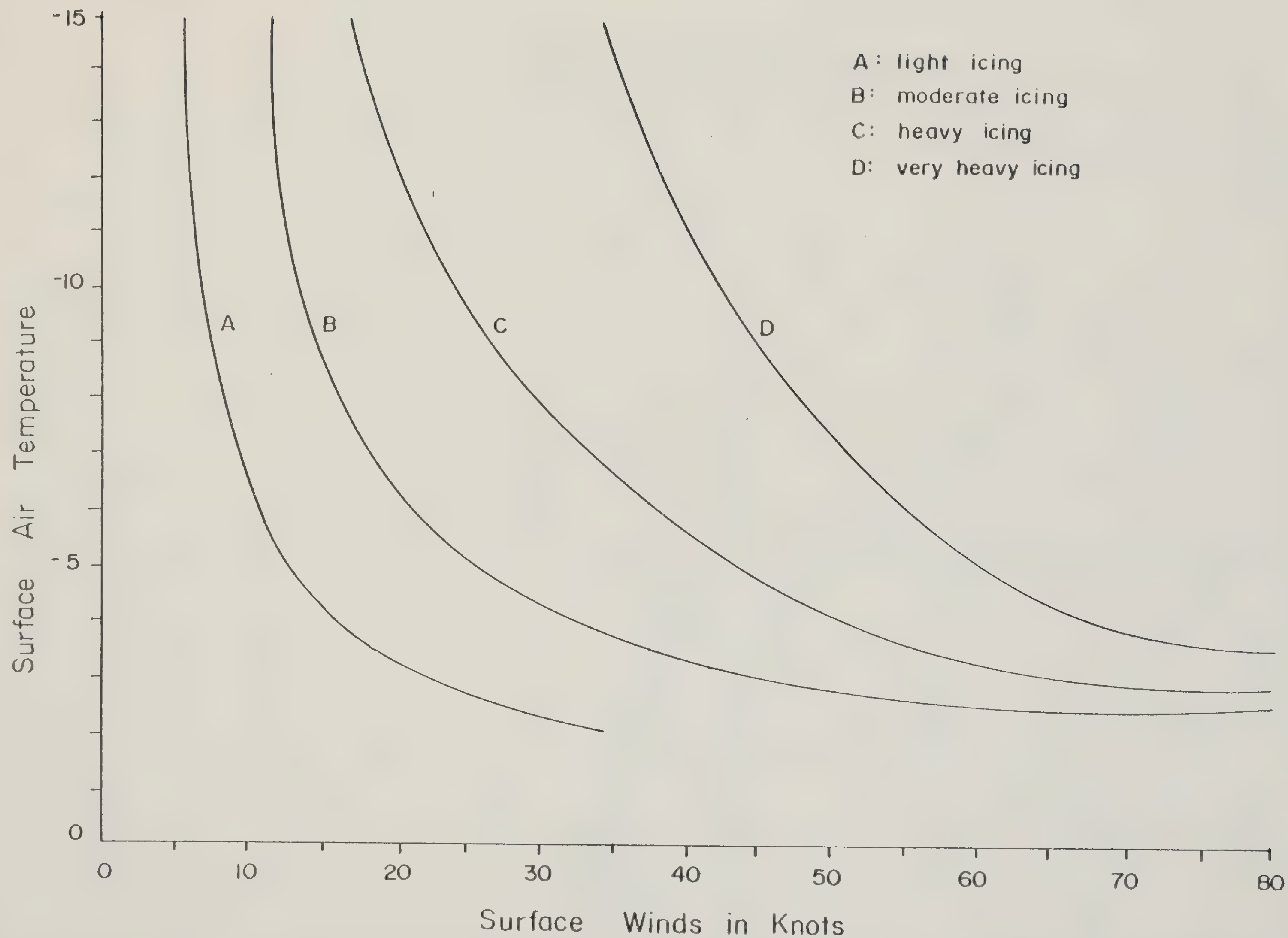

FIGURE 4.2 Ships superstructure icing due to freezing spray (Sawada, 1962)

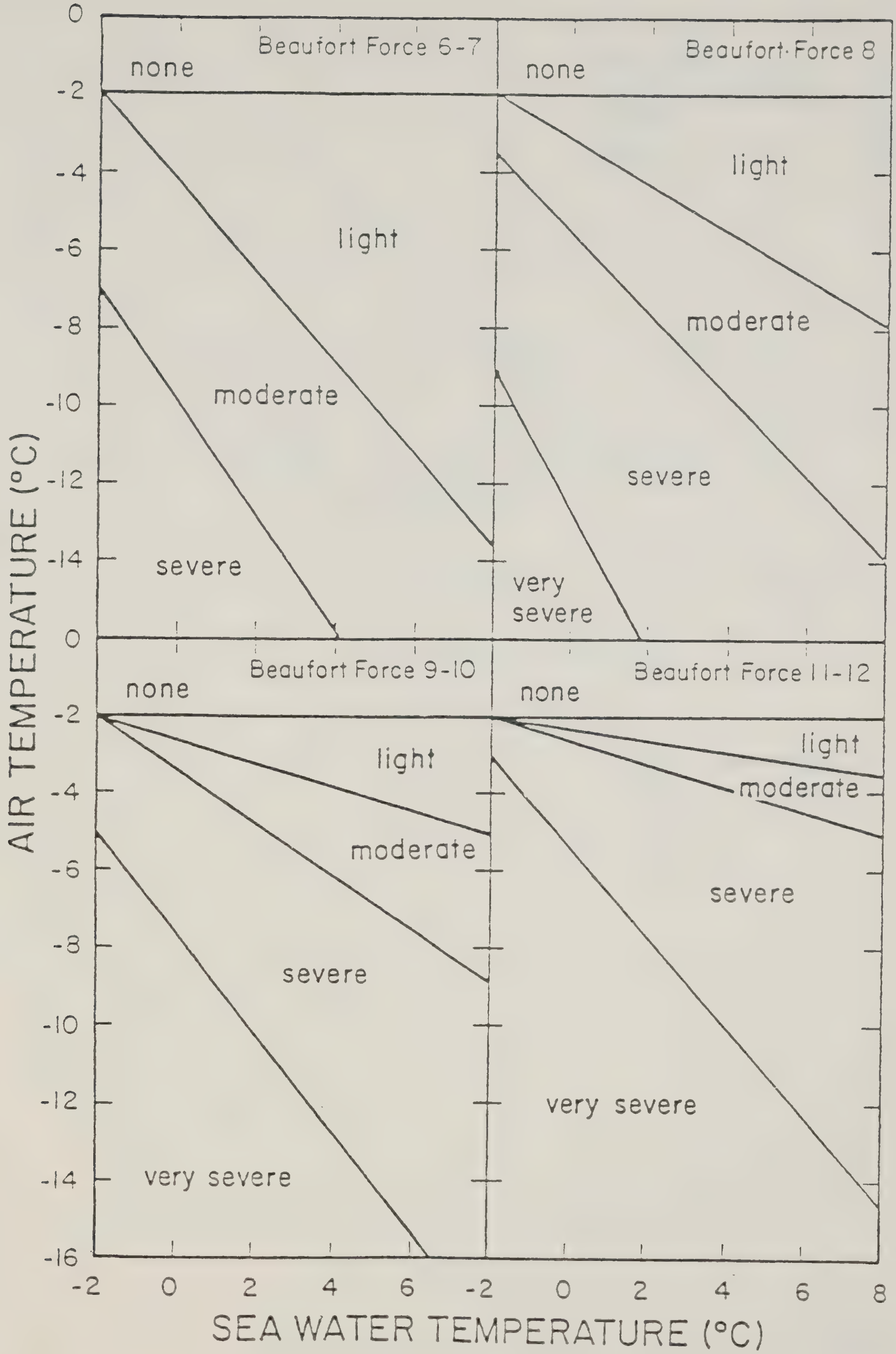

FIGURE 4.3 Ship superstructure icing from freezing spray (Mertins, 1968)

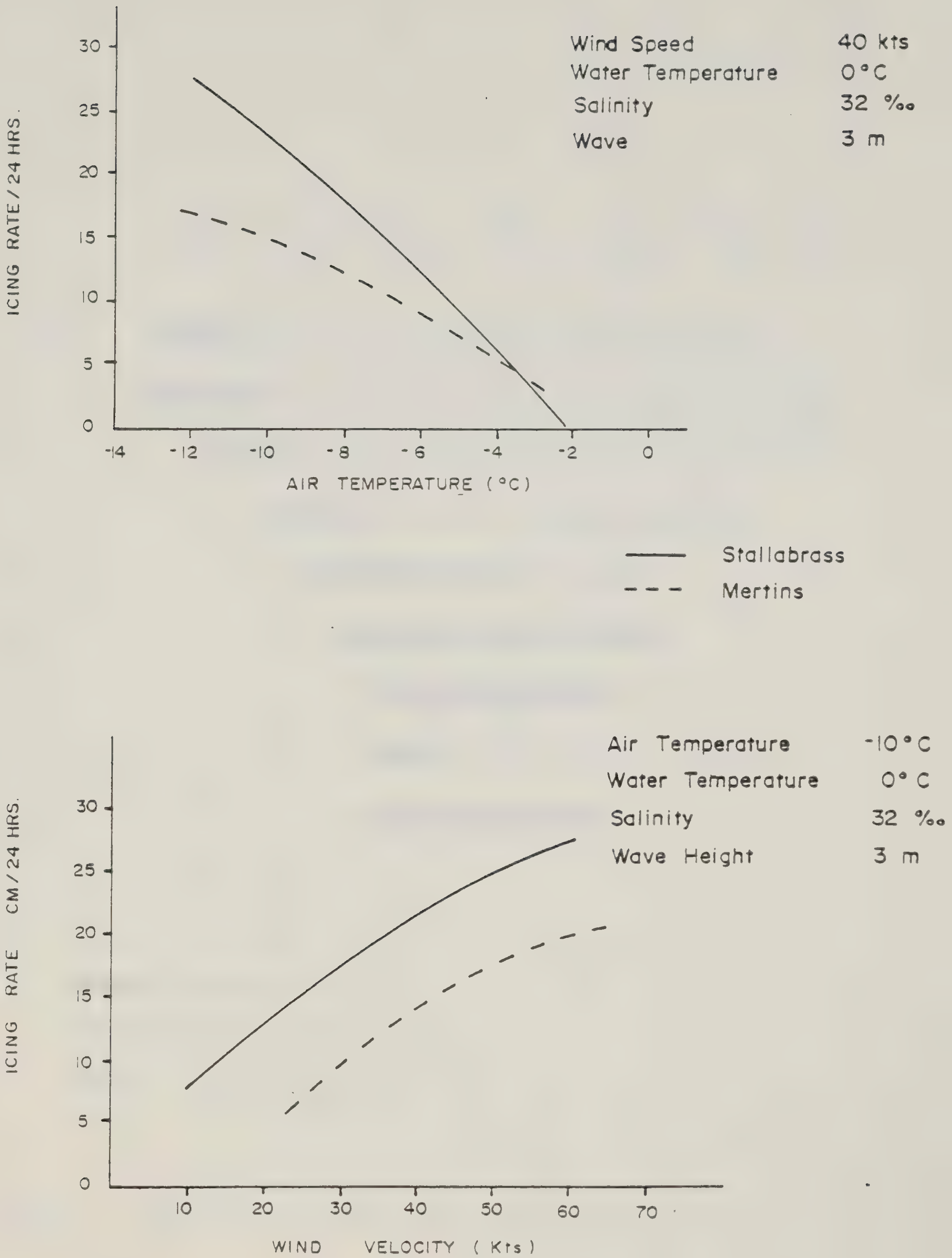

FIGURE 4.4 Comparison between icing rates as predicted using models developed by Mertins (1968) and Stallabrass (198(

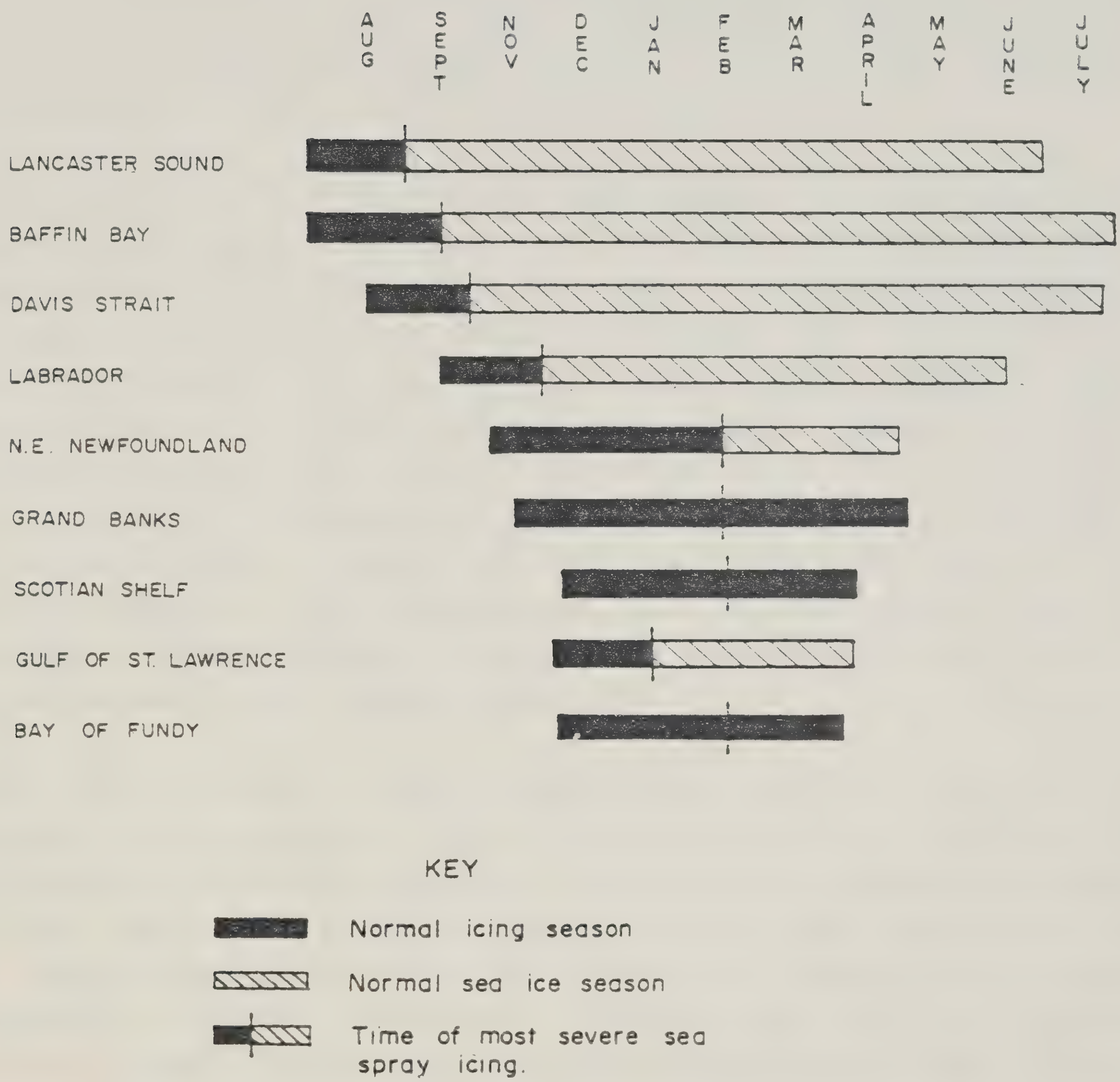

FIGURE 4.5 Monthly occurrence of sea spray icing by region.

excluded since the presence of sea ice reduces the potential for sea spray formation.

It is clear from this figure that sea spray icing is a potential problem in all the regions under consideration and that the most severe icing occurs in February except in areas with seasonal ice coverage when it occurs prior to freeze up.

The actual percentages of observations in different icing categories has been calculated for the Sable Island area and the Hibernia area (Mobil Oil Canada, Ltd. 1981c). In both areas the values were determined by using Mertins' graphs in conjunction with environmental data. The results of these studies indicate that the average frequency of moderate and more severe icing conditions in February (the most severe month) is approximately 8% at Sable Island and 9.5 to 12.5% at Hibernia. No comparable values are available for other areas however, a number of large scale maps are available which show the frequency of icing conditions in the entire study area (DeAngelis, 1974). However, these maps use a different method to calculate moderate and severe conditions.

The Mobil study (1981c) found that the most severe icing conditions at the Hibernia site were experienced in the cold northwest wind behind a low pressure system. This conclusion agrees with results from other areas. The study also found that the most severe conditions were experienced when the low pressure system was centered approximately 500 nmi northeast of Hibernia and that the most severe sea spray icing conditions are not normally associated with the strongest winds. These normally occur when the low is closer to the site. This conclusion may not apply to all other areas off the east coast. The Mobil study also found that the duration of the storm was more important than the maximum severity. The most severe icing conditions were experienced when a severe low pressure system stalled in the Labrador Sea for several days. The presence of sea ice up wind of a site can also increase the severity of icing conditions by allowing colder air to reach the site but the ice can also have a moderating effect if it reduces the wave action.

One of the most difficult problems in estimating icing conditions for offshore areas is calculating extreme events. Since most design work is based on 100 year events it is important to calculate the 100 year icing event. This requires a detailed analysis of all icing events for a period of at least 20 to 30 years. The analysis of icing events is complicated since most ships tend to avoid areas with severe icing conditions. The Mobil Oil Canada study (1981c) searched the available data and identified the most severe event rather than attempting to calculate the 100 year event.

Although environmental factors control the formation of freezing spray, the rate of ice buildup on a vessel is influenced to a considerable extent by the design and mode of operation of the vessel. Some of the more important factors are:

(a) the velocity of the vessel relative to the wind;
(b) the shape and size of the vessel;
(c) the shape of individual structural members exposed to icing;
(d) the nature of the surface coating; and
(e) the heat flow through the surface.

A review of the influence of these factors is found in Minsk (1977).

Due to the uncertainties in estimating the ice accumulation on a particular vessel most regulatory bodies such as intergovernmental Maritime Organization (IMO, 1980) and the Canadian Coast Guard assume a set ice accumulation amounts on different types of surfaces. For example, "Large Fishing Vessel Inspection Regulations" (Canada Shipping Act, 1970 plus regulations) recommend the following ice accumulations for use in evaluating stability:

(a) 11 pounds per sq. ft. (53.8 kg/m^2) of deck area;
(b) 7.5 pounds per sq. ft. (36.7 kg/m^2) for areas of the superstructure exposed to the weather;
(c) 16 pounds per sq. ft. (78.2 kg/m^2) for guardrails, stanchions, hatch coverings and companion ways exposed to the weather;

(d) 32 pounds per running ft. (47.8 kg/m) for rigging, mast, derricks, act measured to a height of 20 ft. (6 m) above the main weather deck.

These Canadian values are considerably higher than those recommended by the International Maritime Consultative Organization, (now known as IMO), 1977 convention.

Comparisons between these regulations and values calculated using models such as Mertins are difficult. A thickness of 6.25 cm of ice on a surface (density of 0.80) is equivalent to approximately 50 kg/m^2 of ice. This ice load would exceed the Canadian regulations presented previously and would be several times greater than the IMO regulations. Based on Mertins diagrams this ice thickness could accumulate in less than 12 hours with very severe conditions and less than 24 hours with severe conditions. For the maximum storm identified in the Mobil Oil Canada Ltd. study (1981c), Mertins diagrams would predict a total ice accumulation of approximately 250 kg/m^2 which is an order of magnitude greater than the Canadian regulations. The data collected by Stallabrass (1980) indicated that events more than twice the IMO standard occured on approximately 2.5% of voyages but values similar to those predicted using Mertins diagrams were not observed. However, it should be noted that a normal vessel would quickly depart the area during a storm of the intensity noted in the Mobil Oil Canada Ltd. study (1981c) and therefore observed values would be considerably less. While the icing regulations may reflect the conditions experienced by a vessel which is free to flee from icing conditions, they may not represent conditions experienced by a supply vessel which must remain by a drilling platform in all weather conditions. The Mobil Oil Canada Ltd. study made certain assumptions regarding the build-up of ice on the work boats and calculated a maximum ice load. Using this value the stability of the work boat was evaluated. It was found that the supply boat experienced stability problems under certain types of deck load and ballast conditions but that under normal conditions the vessel remained stable. These results are based on a number of assumptions

regarding ice build-up and were for a single supply boat design. Further research is needed to clarify this problem.

In addition to stability problems the study (Mobil Oil Canada Ltd., 1981c) pointed out that the ability of the supply boat to perform its functions may be impaired during severe icing conditions. In addition the supply boats own safety equipment such as lifeboats may be inoperative due to ice accretion.

The Canadian icing regulations discussed earlier only apply to large fishing vessels. Similar Canadian regulations for mobile offshore drilling units are only now being developed. The U.K. Department of Energy (1980) regulations give recommended ice accumulations for semi-submersible drilling platforms but these are based on North Sea conditions.

A review of the literature on icing found no observations of ice accumulation on semi-submersibles drilling platforms. A measurement program was carried out in Alaskan waters during 1983 but "unfortunately" no significant icing events were observed (pers. comm. Minsk). There are some indications from unpublished sources that icing events with accumulations of up to several hundred tonnes have been observed off eastern Canada. In addition, observations from Cook Inlet, Alaska will be published shortly but this area experiences different environmental conditions from the study area. (Nauman, 1984).

The lack of reliable observations of icing on semi-submersible drilling platforms precludes a detailed discussion of the factors controlling ice accumulation on these structures, however, a number of factors are clear. The first is the lack of understanding regarding icing on the underside of the platform. This area presents a very large surface area which could accumulate considerable quantities of ice. The second area requiring further research is the vertical profile of icing rates which is an important factor for semi-submersible platforms which have most of the superstructure above

the normal height quoted for the vertical limit of icing (15 m above the wave crest).

The Mobil Oil Canada Ltd. study (1981c) using a number of assumptions regarding the distribution of ice on a semi-submersible platform and the vertical distribution of icing, arrived at a maximum ice load from sea spray icing events of 549 tonnes. The same study also added an additional ice load to this value to account for atmospheric icing and derived a maximum combined ice load of 831 tonnes. The method is sensitive to a number of rig parameters and may give considerably different values for a different rig design.

4.2.2 Icing From Atmospheric Sources

Ice accumulation on vessels, drilling platforms and aircraft can originate from a number of atmospheric sources including:

(a) freezing precipitation (rain and drizzle);
(b) supercooled fog (in cloud icing); and,
(c) wet snow which turns to ice.

Snow which collects on deck areas of vessels and drilling platforms but does not freeze is also considered in this section.

Atmospheric icing, with the exception of ice formation from wet snow, results when supercooled water droplets freeze on impact with a structure. A more complete discussion of the freezing process can be found in Minsk, 1980.

Freezing precipitation results when liquid precipitation is cooled as it passes through a layer of cold air near the surface. It can be divided into freezing rain, which has droplets greater than 0.5 mm in diameter, and freezing drizzle, which has droplets less than 0.5 mm in diameter. Freezing rain has a rate of fall which can range from less than 2.5 mm per hour (light rain) to greater than 7.6 mm per hour (heavy rain) while freezing drizzle normally has a rate of fall of less than 1.0 mm per hour. The considerably higher rates of fall for freezing rain make it a much more serious problem for stability considerations.

Supercooled fog has droplets that are normally from 1-2 micrometers in diameter. Due to its low water content this type of icing is generally not a problem except for fast moving objects (aircraft) or when it occurs in association with high winds. In these cases larger numbers of droplets are brought into contact with the surface. Previous research on the occurrence of icing caused by supercooled fog (Mobil Oil Canada, 1981c) indicates that it is not a problem on the Grand Banks. However no data is available for the northern sections of the study area.

Supercooled fog (in cloud icing) does pose a danger to helicopters operating in offshore areas. However, Canadian Government regulations clearly outline the procedures for dealing with icing situations. The pilots operating in the offshore rely on weather forecasts from AES and reports from the drilling platforms to advise them of potential icing problems. These problems are generally avoided by changing altitude or altering the flight plan. The main situation where icing could pose a danger is in an emergency situation when helicopter support is required or when a helicopter is unable to change altitude due to mechanical problems.

Wet snow which is blown against an object will stick and may change to ice. McKay and Thompson (1969) report a case where 15 cm of rime ice with a density of 0.23 formed as a result of the freezing of wet snow. This type of situation will most commonly occur when air temperatures are at or near freezing. Dry snow can also collect on the deck areas of vessels and drilling platforms. It is unlikely that sufficient snow will freeze or collect on a vessel or platform to cause stability problems but if these situations occur in connection with other types of icing they may compound problems.

The sources of data on atmospheric icing in the study area are meteorological reports from transient ships, drilling platforms and land stations. The observations from transient ships are the largest source of data for the offshore areas but are of limited value for defining the accumulation of ice since these reports seldom provide a continuous record of an icing event. These ship reports can only be used to determine the frequency of different types of events. Drilling platforms do provide a continuous record but the limited amount of data included in the reports and the lack of long term records limits the usefulness of the data. These reports could be improved by adding measurements of the amount of precipitation and the thickness of ice accretion on standard surfaces. While reports from land stations provide more data on icing conditions they seldom provide direct measurements of ice accumulation. To overcome this problem various methods have been developed to compute the ice thickness using wind

speed, air temperature and precipitation observations (McKay and Thompson, 1969; Chaine, 1972; Chaine et al. 1974).

Estimates of the frequency of atmospheric icing for the Hibernia area are provided by Mobil Oil Canada Ltd. (1981c). This study used data from transient ships, drilling platforms and land stations and concluded that the frequency of freezing precipitation at the Hibernia site is low. (under 1% for all months). This contrasts with St. John's which has a frequency of 6.5% in February (the most severe month). However, the low frequency of freezing precipitation cannot be considered as an indication of low potential ice accumulations. Sable Island which also has a considerably lower frequency of freezing rain than St. John's has a higher estimated accumulation on vertical surfaces (Chaine et al, 1974). It should be noted that while the Venture Development Project, Environmental Impact Statement (Mobil Oil Canada Ltd., 1983b) addressed the problem of freezing spray it did not consider freezing rain. There are unpublished reports that one of the largest icing loads observed on a semi-submersible drilling platform in Canadian waters occurred on the Scotian Shelf as a result of freezing precipitation. The Mobil Oil Canada Ltd. (1981c) study also made estimates of the total ice accumulation that would occur on a drilling platform as a result of atmospheric icing at the Hibernia site. The estimate for a 50 year return period was 556 tonnes which is similar to the estimate for freezing spray. It is clear that freezing rain is at least as important a factor for ice loading on semi-submersible drilling platforms as freezing spray.

Estimates of the accumulation of snow on offshore structures are limited by the same problems that are experienced with freezing rain. The types of observations that are made on the platforms do not provide the required data. The Mobil Oil Canada Ltd. study (1981c) used data from land stations to estimate the amount of snow which was associated with the maximum sea spray icing event. This study estimated a snow load of 95 tonnes which represented 17% of the total ice load for this event.

Canadian regulatory bodies do not address the problem of ice loading from atmospheric events on semi-submersible drilling platforms. The British regulations consider both snow and atmospheric icing in calculating ice loads. A value of 50 mm of glazed frost (freezing precipitation) on upward and windward surfaces is suggested as a maximum accumulation from freezing precipitation. These values are comparable with those used for the Mobil Oil Canada Ltd. work (1981c) for the Hibernia site.

The Canadian regulations for ice accumulation on conventional vessels do not specify the source of the icing. The Mobil Oil Canada Ltd. study (1981c) did consider atmospheric icing when calculating the total ice load on the supply boat.

4.2.3 Combinations of Icing Events

When calculating ice loadings on vessels and drilling platforms the possibility of combinations of icing events occurring either simultaneously or sequentially must be considered. The British offshore guidelines (U.K. Department of Energy, 1980) for icing list the following combinations of icing events that should be considered:

(a) Sea spray plus glazed frost (clear ice);
(b) Sea spray plus snow;
(c) Sea spray plus rime (freezing fog); and,
(d) Snow plus rime (freezing fog).

These guidelines go on to suggest that the largest accumulations would result from a combination of sea spray and glazed frost (freezing rain). The Mobil Oil Canada Ltd. (1981c) study for the Hibernia region considered the following combinations of icing events:

(a) Sea spray plus freezing precipitation;
(b) Sea spray plus snow;
(c) Freezing precipitation plus snow; and,
(d) Sea spray plus freezing precipitation and snow.

This study concluded that latter type was the most probable source of the greatest accumulations. The study carried out a detailed comparison of the types of synoptic events that produce each type of icing and found that sea spray events and freezing precipitation events would be unlikely to occur together but that they could occur sequentially. It was also found that these events were relatively independent of each other and so it is unlikely for the maximum sea spray and freezing precipitation events to occur together. The study used the maximum sea spray event which, includes a snow load and 50%, of the accumulation from the maximum freezing precipitation event as a maximum combined event.

4.3 Operations under Icing Conditions

A review of a number of operating manuals carried aboard semi-submersibles and drillships currently being used in eastern Canadian waters shows that, in several, there is no reference to the procedures to be followed in order to mitigate the effects of icing on an offshore unit. In at least one case, specific actions were outlined should ice build-up become excessive. In another, ice loading had been taken into account according to IMO requirements. At least one operator's contingency plan gave clear guidelines as to load dumping priorities and the need for monitoring of ballast condition as the icing load increased.

Clearly, there is an inconsistency of approach across the industry. Where measures were identified, it is unknown at this stage to what extent they are adequate. One, potentially serious problem, that has been encountered is damage to deck equipment at sub-zero temperatures when ice is being removed by hammers or axes.

4.4 Assessment

(i) The database on ice loadings from sea spray is limited and does not permit the accurate calculation of "100 year events".

(ii) Empirical and theoretical models have been developed for the prediction of sea spray icing on vessels, but comparisons suggest that results reflect the type of vessel studied in the particular database and are not transferable to significantly different types of vessel.

(iii) Using an empirical formula plus environmental data, the occurrence of moderate or severe sea spray icing conditions is estimated to occur 8% of the time for the Sable Island area and 9.5% to 12.5% at Hibernia during the most severe month - February in both cases. Only general information in the form of maps appears to be available outside these two areas.

(iv) Formation and rate of build-up of sea spray ice is a function of vessel shape and size, the shape of structural members exposed to icing, the nature of the surface coating, and the heat flow through the surface. Most regulatory authorities give no guidance on ice build-up and limit themselves to specifying the maximum allowable ice accumulation to be used in stability calculations.

(v) Icing data for semi-submersibles is virtually non-existant, and there is no clear understanding of ice accumulation on the underside of deck areas, or on changes in accumulation rates up the sides of vertical or inclined columns.

(vi) The database for atmospheric icing events (freezing precipitation, supercooled fog, and wet snow turning to ice) is not sufficient to calculate meaningful "100 year events".

(vii) There are indications that for some areas the accumulation of ice on drilling platforms due to freezing precipitation may be as important as the accumulation from sea spray.

(viii) Some of the operating manuals reviewed in the course of this study make no reference to icing of any type, whereas others detail actions to be taken, including load dumping priorities.

(ix) Total icing loads with a 50 year return period in the Hibernia area have been estimated to be 550 tonnes from sea spray icing, with a maximum load, taking into account atmospheric icing, of about 830 tonnes. However, these values depend heavily on a number of rig parameters and the model used to estimate extent and rate of accumulation of ice.

(x) A formal record of ice build-up on drilling platforms at different locations and operating under different environmental conditions is urgently required.

5.0 ICE DETECTION

5.1 Introduction

Current East Coast drilling practice assumes all ice will be detected in sufficient time to take any action necessary to ensure the safety of the operation under any weather condition or drilling situation. The drilling platforms rely upon marine radar as the primary ice hazard detection device when conditions preclude the use of visual observations.

Floating ice is restricted to the winter months in the Gulf of St. Lawrence and rare on the Scotian Shelf. Therefore, until winter drilling is proposed for the Gulf, the detection of floating ice is not a significant problem in these southern areas. However, floating ice in the form of icebergs or sea ice represents a real potential hazard to all ship and drilling operations throughout the area from the Grand Banks northwards. Consequently, it is essential that potentially hazardous floating ice be detected and reliably tracked under adverse atmospheric and oceanographic conditions in sufficient time to take any action necessary to ensure the safety of the operation in this region.

Airborne visual observations are used to provide information on upstream conditions. Occasionally, and more on an experimental than an operational basis, Side Looking Airborne Radar (SLAR) systems are employed for both pre-season and operational reconnaissance. However, an operational SLAR reconnaissance program is planned for the Grand Banks during the winter and spring of 1984.

The marine radars in use range from the basic systems supplied by the offshore platform (usually a X- and a S-band system) to special systems supplied by the operator which employ special frequency combination capabilities and Automatic Radar Plotting Aids (ARPA). On some of the platforms antennas are placed on top of the bridge's radio room or control room, while on others, the derrick top is utilized.

It is noted that although these ARPA systems do employ special processing for automatic target detection, discussions with NORDCO Limited ice observers experienced in their use indicate that there is no noticeable improvement over conventional radars for the detection of icebergs.

Airborne visual reconnaissance flights in the Grand Banks/Hibernia region are normally flown as long as there are icebergs present. The offshore operator apparently makes the decision as to where and when any given flight occurs. Off Labrador, flights are normally only conducted before or at the beginning of the drilling season to monitor the sea ice break up. Once the pack ice is gone these flights usually stop.

Occasionally, reconnaissance information from other agencies is utilized. This includes information from International Ice Patrol (IIP) and Atmospheric Environment Service (AES) flights. Normally no dedicated flights are made by these agencies and the information is supplied on an opportunity basis when they are operating in an area of interest. However, the AES now has a mandate to considerably expand its ice and iceberg programs.

Very limited quantitative work has been done on assessing the performance of the various ice detection devices currently being employed, at least as far as the open literature is concerned. However, there have been and are currently ongoing a number of government and oil industry sponsored R&D programs intended to establish the theoretical and practical limitations of currently available equipment for ice detection, and for the development of novel ice detection systems. The following sections summarize the results to date.

5.2 Performance of Floating Ice Detection System

5.2.1 Icebergs

A review of the historical literature shows that icebergs are poor radar reflectors (e.g. Hood, 1958; Budinger, 1959; Budinger, 1960; Williams, 1979). This results in two detection range limitations. The maximum range of detection is limited because of the low signal return, and short range detection is limited because of competing sea clutter return. Figure 5.1 is a summary of the detection performance compiled from the work of a number of researchers. This graph shows the maximum range of detection versus projected area of the iceberg (area projected onto a plane normal to the incident radar beam). Estimates of this projected area were used to fit Miller's (1982) and Pearson's (1982) data on the graph. The figure should not be misconstrued as indicating that all targets were detected, rather it provides range of detection information for those that were detected.

Figure 5.1 warrants some discussion. The data used by Hood (1958) and Budinger (1960) to construct their curves had a significant spread, as is demonstrated in Figure 5.2. The spread in the data provided by Miller (1982) and Pearson (1982) compare well with that obtained by Budinger and Hood. Therefore considerable caution has to be taken when applying the results in Figure 5.1 on an operational performance assessment.

Budinger's work was undertaken as a dedicated program using predominantly military radar systems, while the rest employed commercial radars. Hood's work involved the collection of data from many different vessels while Miller's results are from a dedicated scientific program in the Eastern Arctic using essentially state-of-the-art technology and a complex radar system configuration (Jonasson et al., 1981). The data obtained by Pearson (1982) were apparently obtained during normal operations on a drillship in the

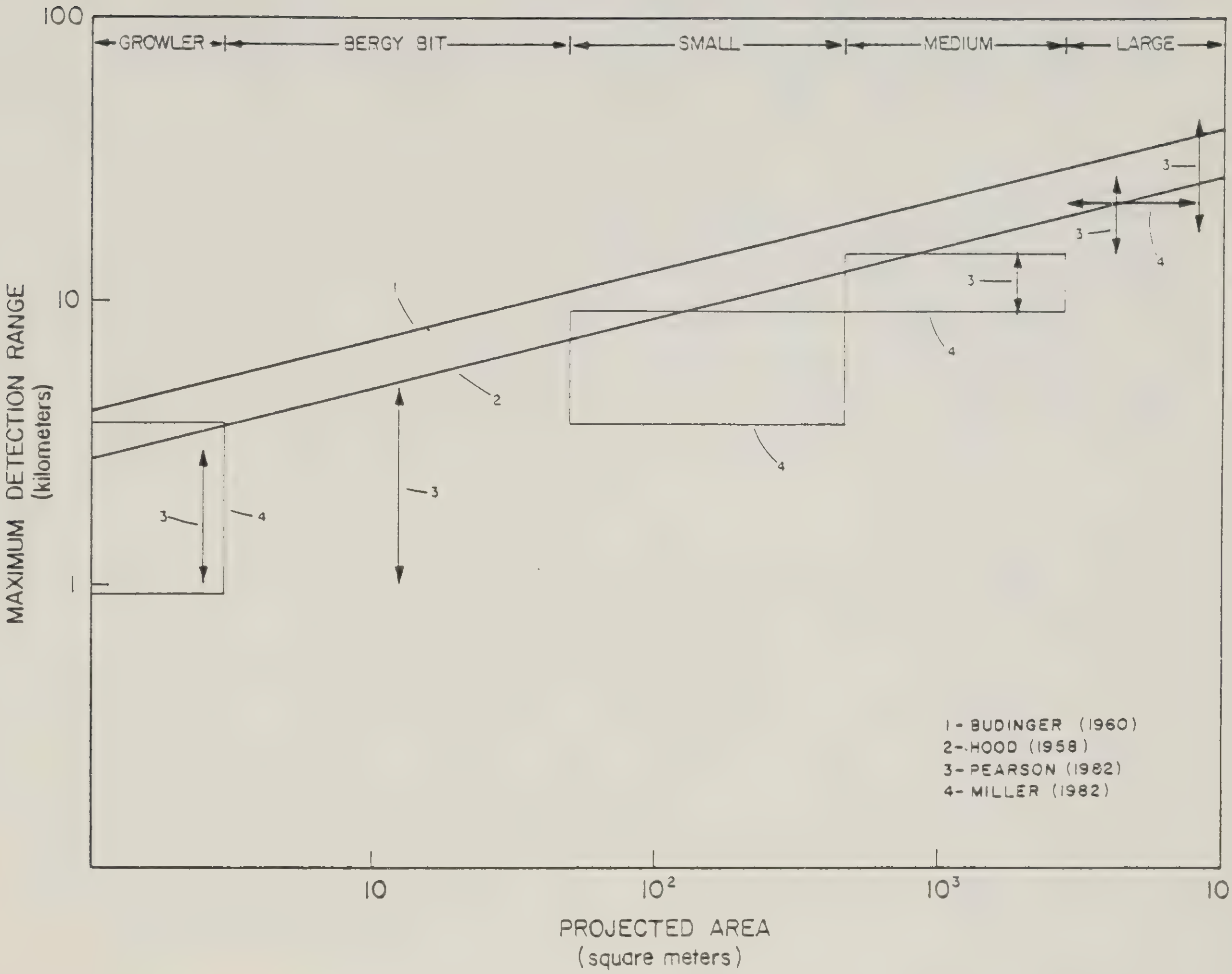

FIGURE 5.1 - SUMMARY OF X-BAND MARINE RADAR DETECTION CAPABILITIES OBTAINED THROUGH VARIOUS STUDIES.

Labrador Sea. Therefore, Figure 5.1 gives a good assessment of the change in the maximum range of detection performance over a period of about twenty-five years. Over all, it indicates that, as far as this aspect is concerned, commercial radars in use today are only equivalent to or even slightly less effective than those available in the 1950's.

Using a range of reasonable antenna heights (15 to 30 m) it is seen that, with the exception of Budinger's curve, most icebergs (considering the data spread) except the large size class were detected within the radar horizon and probably the visual horizon. In other words, visibility permitting, most icebergs will be seen visually before a radar detects them. This observation has been made by a number of researchers.

Finally, caution was expressed by Hood (1958) that the curves shown are probably not applicable for assessing growler detection ranges. A growler generally has a freeboard up to 1 m and horizontal dimensions to 6 m. These targets are normally only detected when in or close to the region of strong sea clutter and therefore their detectability is governed by the operator's ability to discriminate the growler signal from that of the surrounding clutter. As indicated in Figure 5.2, this can cause wide fluctuations in the range of detection within this region.

Hood (1958) stated that under normal conditions with sea clutter extending out to slightly less than 2 km, an ice fragment large enough to inflict damage on a ship will be detected beyond this zone. He also reported that out of a total of 54 growlers only 22 were detected by radar and then only outside the clutter. None were detected within the clutter and some detected outside the clutter area were lost upon entering it. The largest growler was detected out to a range of 5.5 km. Budinger (1960) could not detect growlers beyond 7.4 km. In his conclusions, he stated that waves in excess of 1.2 m might obscure a dangerous growler even with the expert use of clutter reduction controls (these same controls are in use today). Also, he concluded that if an ice target is not detected outside the clutter then it will

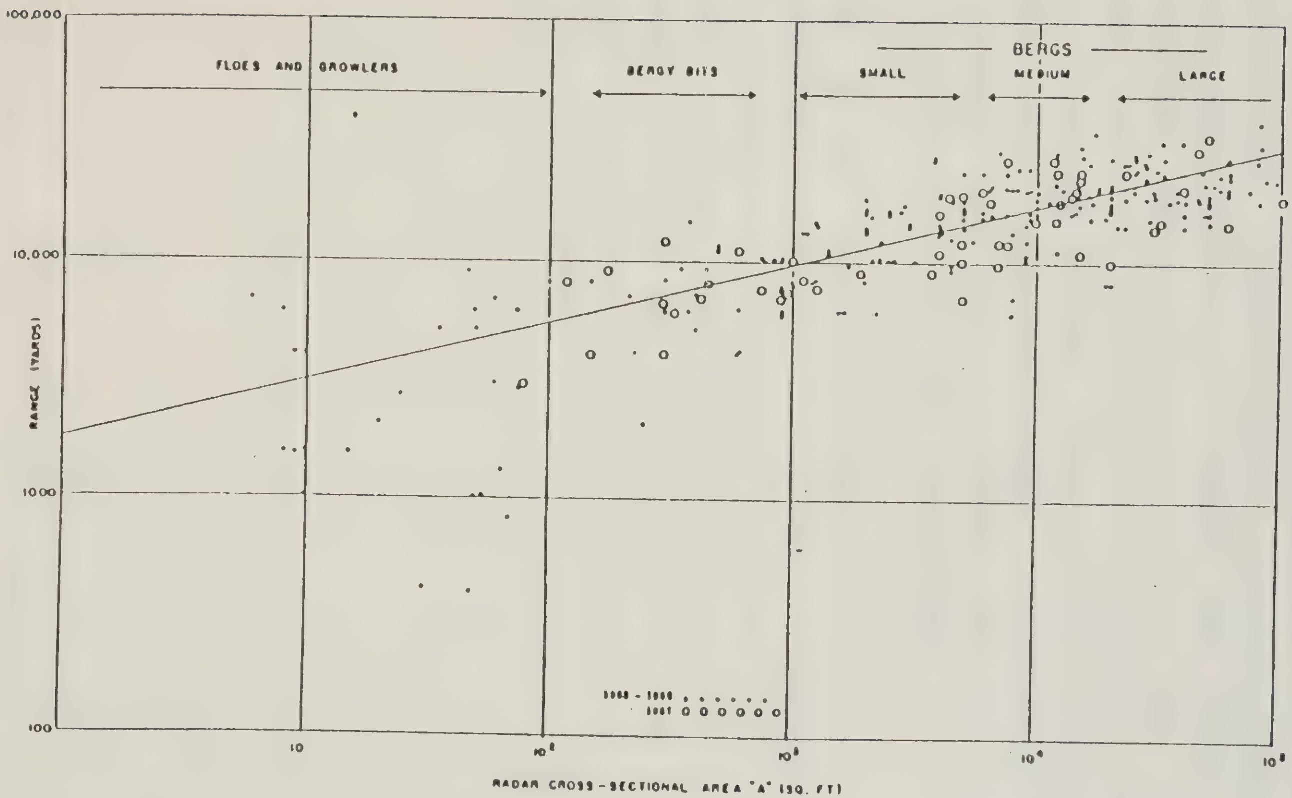

FIGURE 5.2 - MAXIMUM RANGE OF DETECTION VERSUS AREA FOR X-BAND MARINE RADAR (HOOD, 1958)

not be detected at all. Williams (1979) reported similar detection ranges. From the preceding, it can be assumed that there is about a 50% probability of detection for growlers outside the clutter region and the absolute maximum range of detection is in the order of 5 to 7 km. As a clutter region extending out to 2 km is probably the norm this indicates that there is only a circular annulus about 3 to 5 km wide 2 km from a platform or vessel when there is any significant possibility of detecting a growler. In high sea states causing significant clutter out to 5 km or greater, the probability of detecting a growler is then virtually nil. It was also reported by Hood (1958) that, on one occasion, a gale caused significant sea clutter to extend out to about 15.0 km and this resulted in icebergs about 30 m high being rendered undetectable.

Buckley et al., (1982) provided a good operational assessment of marine radar for iceberg detection in the Labrador Sea. It was stated that on a dynamically positioned drillship X- and S-band radars are the primary detection and tracking devices for all ice. It was found that S-band radar was better for long range detection and thus was utilized more for tracking and surveillance. X-band radar was better for detecting small pieces of ice within a few nautical miles of the rig. Large icebergs were observed to give strong returns and then sometimes later very weak echoes. However, it was noted that large icebergs were usually eventually detected and that the real problem was detecting bergy bits or growlers. Except for very large icebergs, the maximum range of detection was found to be 18.5 km for all practical purposes. The returns from the bergy bits and growlers were said to look very much like rain or sea clutter and they could easily be obscured by clutter even in moderate sea states. It was said that in actuality, reconnaissance by patrol boat was the best method for detecting growlers given the present state of the art in commercial marine radar. The authors suggest that other sensing devices are required for iceberg detection besides commercial marine radar.

REMOTEC Applications, Inc. in 1982 prepared radar configuration guidelines for iceberg detection from offshore drilling platforms for the Newfoundland and Labrador Petroleum Directorate (1982d). The

report recommended four configurations, the minimum acceptable one consisting of one X- and one S-band radar mounted as high as possible on the platform. The most complex configuration included a low resolution X-band radar in addition to the conventional X- and S-band systems. It was recommended that the scanner for this additional radar should be mounted, if possible, at a height lower than the other X-band scanner, and at least one X-band radar should have switchable circular horizontal polarization.

The report noted that evaporation ducts can exist over the surface of the ocean in the North Atlantic, with the median upper boundary of the duct being 10 m high in the summer and 30 m in the winter. Small targets having heights less than the duct height may not be detected if a radar scanner is located above the duct.

In the conclusions and recommendations of the report, it was noted that detection performance was highly dependent on the training and experience of the radar operators and that motivation and constant vigilance must be maintained to ensure the best reliability. It was also stated that these operators should be trained not only in the basic operation of the radar systems, but also in the subtleties and basic theory involved.

Ryan underook a study of current iceberg detection capability under contract to the Newfoundland and Labrador petroleum Directorate (1983d). Although other sensors were discussed, the study concentrated on marine radar. Extensive theoretical modelling was undertaken to determine maximum detection ranges under various environmental conditions. An iceberg cross section model based on Budinger's (1960) work was utilized. However, it has been shown that there is a major error in this earlier work (Dawe, 1983; Hammond (Ice Operations Division, U.S. Coast Guard, Washington), pers. comm. 1982) thus invalidating many of Ryan's conclusions. For example, a range of detection of 15 kilometres in a sea state zero was given for a growler. This is approximately double that found in actual measurements and shown in Figure 5.1. To obtain the best detection capability a radar configuration almost exactly the same as that

recommended in the Newfoundland and Labrador Petroleum Directorate contracted study (1982d) was suggested along with the addition of a Japan Radio Corporation (1982) sea ice processing unit.

Other than the growler detection results by Hood (1958), there is no quantitative information available regarding the detection capability versus range under any given set of environmental conditions for any given iceberg target. This shortcoming has been recognized by both the oil industry and the government and a major project is planned to take place in 1984 with this being one of its objectives (Dube and Ruel, 1983).

Finally, subnormal propagation conditions are known to exist in the Hudson Strait region (Le Page and Milwright, 1953) and in the Grand Banks region (Budinger, 1959, 1960). This will result in a reduction in the radar detection range; but, a quantitative assessment of the actual effect on target detection is not available.

The major problems in utilizing airborne visual observations for "upstream" reconnaissance is the predominance of poor visibility conditions, particularly in the Grand Banks region. The lack of visibility can result in cancelled flights, and it limits reconnaissance capability when flights do occur. The International Ice Patrol (IIP) has found this to be a significant problem and has developed longterm drift models for icebergs in its area of operation in order to provide some positional information during periods when reconnaissance is prohibitied (e.g., McClelland and Sturm, 1983). The IIP is now testing and utilizing a SLAR on a semi-operational basis to provide almost all weather capability (Howes, 1979; Super and Osmer, 1976). Ice Branch of the Canadian Atmospheric Environment Service (AES) has been using SLAR on an operational basis since 1977. Although the primary role of this latter system is sea ice reconnaissance it is used to provide information on icebergs when they appear in the area of interest and increasing attention will be given to icebergs in the future. The offshore oil industry and the Canadian Government have recognized the limitations of visual reconnaissance, and, as such, a major industry/government program is being launched in 1984 to assess

the utility of imaging radars for iceberg detection (Dube and Ruel, 1983).

SLAR was tested on an experimental basis for iceberg reconnaissance on the Grand Banks by the United States Coast Guard (USCG) through the International Ice Patrol (IIP) as early as 1957 (Super and Osmer, 1976). A real time radar image processing system was recently developed by the USCG to use with a SLAR and the sytem was shown to be able to detect small icebergs consistently out to 48 kilometres (Super and Osmer, 1976). In fact, detection of all targets was not considered a problem; although, target identification was not possible. The USCG has been and is still continuing to work on the identification problem (Marthaler and Heighway, 1978; Howes, 1979). On the other hand the Ice Branch of the Atmospheric Environment Service (AES), using virtually the same SLAR with only a photographic real time output, reports detection capabilities of only 40 to 50% in a sea ice background (Lapp, 1982). Results from these and other studies (Ramseier and Lapp, 1980; Swift and Crawford, 1981) indicate that widely varying detection capabilities are possible, and, in the two cases reported, the results suggest that the detection problem is related more to the data output format than to the radar itself. Image enhancement work on historical AES SLAR imagery undertaken by REMOTEC Applications (1983) indicates that this may indeed by the case. Other studies have shown that at certain ranges of incidence angles and in higher sea states icebergs may be rendered undetectable because of a low signal-to-background clutter ratio (e.g., Gray et al., 1979). There appears, however, to be general agreement among researchers that the major factor limiting iceberg detection and identification with a SLAR is its poor areal resolution. As noted earlier, a major study is to be launched in 1984 to determine quantitatively the detection capabilities of SLAR.

Supply boats are also used for visual reconnaissance. However, poor visibility restricts their effectiveness as well. Their slow speed combined with the limited visual observation range further reduces their utility for iceberg reconnaissance.

5.2.2 Sea Ice

Observations by a number of researchers based on data collected in the Eastern Arctic (e.g., Perry, 1953; Le Page and Milwright, 1953; Hood, 1958) indicate that broken and hummocked ice could be detected by marine radar out to ranges of around 5 to 8 km. Le Page and Milwright (1953) were able to detect leads at 4 to 5 km ranges, however, Perry (1953) was unable to reliably detect leads at all. They also stated that once in the ice field, the radar return took on the appearance of sea clutter. Such detection capabilities were said to not apply to smooth ice conditions. Hood (1958) suggested that the detection of ice fields would not be difficult because the ice tends to dampen the sea clutter, thereby providing an area of reduced return on the radar screen. He also found that all of the 13 individual floes reported were detected at ranges greater than 3.6 km, noting that even in rough sea conditions the edge of a floe gave a sharp demarcation line. This is opposite to that stated by Perry (1953) who said that ridges and straight faces resemble sea clutter and although detectable in calm seas, they might be missed in the presence of rough seas or swells. Williams (1973, 1979) presented results comparing sea ice detection with high and low resolution radars. So called ribbon ice was detected out to 22 km in a sea state of about 3 with the high resolution set, while the low resolution set gave detection ranges of 3.7 to 7.4 km. Petro-Canada (Miller, 1982) gave the same ranges of detection as these latter values for individual ice floes. Intera Environmental Consultants Ltd. showed examples indicating that, by mounting a radar antenna on top of a drillship derrick operating in the Beaufort Sea, sea ice topographic features could be detected out to 22 km using special processing and a video display (Intera Environmental Consultants, 1983a; Raman et al., 1983). C-CORE (1983) reported ranges of 11 km in the Beaufort using surface based systems and a special gray level video display.

It appears then that rough, consolidated pack ice can be detected at ranges out to about 20 km from radars with antennas mounted on derrick tops, while on ships, the range is in order of 8 km. Loose pack ice conditions can be confused with clutter and individual floes

have detection ranges similar to those of growlers. However, almost all the results were obtained in Arctic regions and may not apply to more southern areas such as the Grand Banks where subnormal propagation conditions are known to dominate and the ice characteristics may be very different.

None of the results to date suggest that classification by ice type is possible. However, it has been shown through measurements from airborne imaging radars and scatterometers that at the angles of incidence associated with marine radar, ice topography is the dominating factor in the returns received (e.g., Gray _et al._, 1977; Hengeveld, 1980). This necessitates further study as loose first year ice may not present a significant hazard, but hard multi-year ice within a pack could go undetected. The same could be said for growlers and icebergs within the pack ice.

Finally, as with icebergs, there appears to be no quantitative information regarding the detectability of a given target type at any given range under a given set of environmental conditions. This information is required in order to obtain data on collision probabilities.

Basically, the same visual reconnaissance techniques are employed for sea ice as with icebergs. Because sea ice is usually a large scale phenomena, the problems of detection, monitoring, and tracking are considerably reduced. Therefore, from a long range strategic point of view this is not considered a problem.

As stated earlier, SLAR has been used for sea ice and iceberg reconnaissance by AES since 1977. SLAR has been found to be an excellent tool for mapping sea ice in all ice infested waters. It has also been proven useful in detection and classification of ice types and various other characteristics (ridges, rough ice areas, floe sizes, etc.). Its virtual all weather day/night operational capability limits its utility only when conditions are such that the aircraft cannot fly.

5.3 Current Research and Development

Transport Development Centre (1983) had recently prepared a detailed report on current research and development activities regarding the detection of ice hazards. Briefly, it shows that most of the research is directed towards marine radar and HF (high frequency) multistatic radar. Only one company was doing research on multisensor surface based systems (radar, sonar, infrared scanners, etc.) and this work is being continued by NORDCO Ltd. Except for the HF radar long range detection system, all the research is geared towards close range detection (within the visual horizon). Some of the marine radar processing and display systems are currently operational but none have been tested on an offshore platform off the east coast. However, these systems are geared toward static or slow moving sea ice situations (i.e., large scale phenomena), and may not even be useful to this region.

One portion of the Newfoundland and Labrador Petroleum Directorate study (1983d) also provided an excellent detailed discussion of on-going research related to the development of ice hazard detection systems. Although, considerable research was seen to be on-going, only the Japan Radio Corporation (1982) has a marine radar system commercially available which, from data presented in company brochures, shows a clear improvement in the detection of sea ice and individual targets in a sea clutter background.

Petro-Canada reported that in its major ice hazard detection program theoretical evaluations of sonar, infrared and low light level television were made (Jonasson et al., 1981). Because of budgetary restrictions only the first two were tested along with marine radar in their 1980 field program. No results were presented for the sonar except to say that a variable depth system seemed warranted. Miller (1982) presented suggested sonar parameters for ice detection based on the same program. The infrared system was found to be useful and detection results were also presented by Miller (1982). The status of the research in this program is unknown at this time, although Viatec Inc. is currently undertaking an evaluation of the data collected for

the Transport Development Centre (Ryan, 1983).

The first field test of the HF radar will probably not take place for another year and there is no indication that any of the new marine radar techniques or any other sensors will be tested for at least another two years. In 1984, the federal government will be launching a project to assess marine radar for the detection of icebergs from drilling platforms (Dube and Ruel, 1983). This study will hopefully provide quantitative data on detection capabilities and may shed some light on the requirements of an optimum system.

SLAR and SAR (synthetic aperture imaging radar) have both been used operationally for sea ice reconnaissance in support of drilling programs in the Beaufort Sea. However, the ice conditions in the Beaufort Sea are considerably different from those encountered off the east coast of Canada and icebergs are not a problem (although some ice islands are present in the region). Both systems will be evaluated for iceberg detection on the east coast in 1984 (Dube and Ruel, 1983). SAR has been tested experimentally for iceberg reconnaissance in the Eastern Arctic (e.g., Lowry and Miller, 1983; Gray et al, 1979) and shows considerable promise. The object of the experiment planned for this year is to test all imaging radar systems currently operationally available for their iceberg detection capability. Again, this should provide some quantitative data on the detection of icebergs and some insight into an optimum system.

Canada is planning to place a satellite in orbit in the late 1980's or early 1990's which will carry a SAR system (RADARSAT, 1982) and much of the ongoing experimental airborne SAR research is dedicated towards determining the specifications for the spaceborne system. It is doubtful, however, that one satellite will provide the temporal and spatial coverage necessary to provide the all weather day/night ice reconnaissance required to operationally support ongoing offshore drilling programs. Also, the resolution and limited incidence angle range of the SAR imaging system may render it unreliable for iceberg reconnaissance.

5.4 Assessment

5.4.1 Icebergs

(i) Icebergs of any size are poor radar targets.

(ii) The presence of clutter, especially sea clutter, is the major limiting factor in the detection of icebergs when at ranges shorter than the maximum. This presents a serious problem in the detection of bergy bits and, in particular, growlers, as they are normally only detected at short ranges, and even in low to moderate sea states the clutter may be sufficient to mask them at their maximum ranges.

(iii) In the absence of clutter there is a direct relationship between the size of the iceberg and the maximum range of detection. The tremendous scatter in the range of detection data provided by the various researchers suggests that caution is necessary in applying the relationship.

(iv) Subnormal propagation conditions dominate in the Grand Banks region. There is very little information available regarding the conditions in the more northern areas. There is a need for more quantitative information for all areas.

(v) The level of on-going R&D indicates there is recognition of the need for improvement in marine radar for the detection of icebergs.

(vi) None of the research reported here provided significant information on the number of icebergs not detected at all on marine radar. This has created the false impression that only small targets in clutter go undetected. However, it has been the experience of marine interests in these waters that quite frequently icebergs of almost any size and at moderate ranges do go undetected. This is difficult to quantify but the need exists to determine the percentage of time and the conditions under which this situation might occur.

(vii) Given the predominately poor visibility conditions, particularly on the Grand Banks, there is some question regarding the effectiveness of airborne visual reconnaissance.

(viii) Long range visual reconnaissance by surface vessels will also be restricted by the poor visibility and the short coverage area observed at any given time.

(ix) The effectiveness of short range visual reconnaissance by support vessels in the vicinity of a drilling platform at times of low visibility or in darkness is unknown. Larger ice targets may be detected but growlers may still not be sighted under these conditions. During rough sea conditions the movements of the support vessel may be restricted, reducing its capability to perform reconnaissance work when it is most needed.

(x) SLAR, because of its all weather, day/night capability, has the potential of being a very valuable reconnaissance tool, but there is considerable confusion regarding its true detection capability against essentially point targets. As with marine radar this capability needs to be quantified.

(xi) A major limitation with SLAR is the problem of identifying targets. In areas such as the Grand Banks there is significant fishing and marine transport traffic. Thus, the probability of false alarm is significant, at least in this region.

5.4.2 <u>Sea Ice</u>

(i) The detection range for sea ice floes appears to be similar to that for small icebergs and growlers. Signal processing techniques and

high antenna heights have been shown to improve topographic feature detection ranges for consolidated pack ice in the Beaufort Sea, but this may not apply for the East Coast of Canada.

(ii) Because unconsolidated or loose pack ice may take on the appearance of sea clutter on marine radar it may be difficult to detect under certain conditions.

(iii) The inability to identify ice types in the sea ice pack using marine radar may prevent detection of potential dangerous multi-year floes.

(iv) Because pack ice is generally a large scale phenomena, visual observations, either from ship or aircraft, should be adequate for monitoring it, and poor visibility should not present a major problem. The detection of multi-year floes should also be possible but well trained observers will be required.

(v) The almost all weather day/night reconnaissance capability of SLAR makes it an ideal instrument for the reconnaissance of sea ice. It is also capable of providing classification of ice types and accurate positional information.

5.4.3 General Considerations

i) Individually, each detection method has its shortcomings. The performance achieved through an integration of all the techniques may be adequate but there is insufficient evidence to make an accurate quantitative assessment. For long range strategic reconnaissance upstream of a drill site, it would appear that the combination of both airborne and ship based visual reconnaissance along with SLAR might be adequate. However, SLAR would have to be employed on a dedicated basis rather than as a tool of opportunity employed by another agency. With the integration of all these methods, however, small and dangerous targets may still slip through undetected.

ii) For short range close tactical monitoring there are a number of problems. Under moderate sea conditions, with even moderate to poor visibility in daylight, the combined use of marine radar and diligent visual reconnaissance (from the drilling platform and service vessels) should make it possible to detect and keep track of all ice hazards. Under severe low visibility weather conditions and in darkness, visual reconnaissance will be impossible. Marine radar will have to be relied upon almost totally. Unfortunately, marine radar is least reliable under severe weather conditions and ice hazards may approach undetected. As noted earlier, it should be relatively easy to track sea ice and this is applicable even at short ranges from the drilling platform. The problem at close range is that small icebergs, growlers, multi-year floes, etc., within the sea ice pack may go undetected when reliable detection and precise positional information is most necessary. The presence of darkness, low visibility and/or rough seas will compound this problem.

6.0 ICE AS A FACTOR IN REGULATIONS AND CLASSIFICATION

6.1 Introduction

Steel as a structural material is ideal for use in the hulls of vessels operating in ice with the precautions that it be weldable quality and that its low temperature properties are suitable to the area of operations. This is easily achieved by careful design. There was a time, before such problems were understood, which was remarkable for the loss of many wartime merchant ships. This spectacular breaking-in-two of ships is a cold water/weather phenomenon now fully understood and not related to ice.

To permit vessels to sail with reasonable insurance premiums when they were inadvertantly caught in a harbour that froze unexpectantly, the Classification Societies many years ago issued rules for strengthening for navigation in ice (e.g. American Bureau of Shipping, 1950). This amounted to a little extra stiffening at the bow and was barely an improvement in the operational capabilities of such vessels.

When serious attempts were made to extend navigation seasons into or through the winter months, the Classification Societies each separately published rules which were remarkably similar and are typified by Lloyds Ice Class 1, 2 and 3 (Lloyds Register of Shipping, 1982). Class 3 is negligible and comparable to the old Strengthened for Navigation in Ice, but Class 1 is reasonable for many ice operations and calls for stiffening the hull from bow to stern. These regulations also specify the minimum power of the vessel for classification and require larger diameter propeller shafts and rudder stock.

To go back again to early days before the turn of the century, there was a developing consensus of an "icebreaker" classification. This was mostly intuitive and based upon experience and used either for winter ferries or coast guard type ships which, by mid-century, would work in the St. Lawrence River in winter and spring, and go

north in summer and fall. The new "ice rates" referred to were insufficient for the rating or classification "icebreaker."

When the voyage of "Manhattan" in 1969 was being planned it was made clear that good data on both ice properties and ship structure and form were almost non-existant. What there was, was not organized or stored in retrievable fashion, but was scattered about in the possession of a few individuals. The "Manhattan" voyage (Gray and Maybourn, 1981), with its preliminary studies and data collection, began a period throughout the 1970's of tremendous interest and investigation into the problems of structures for navigation in ice. Immediately following was the Arctic Pilot Project (Arctic Pilot Project, 1981) to carry LNG by sea from the Arctic Islands. The formal application and ancilliary studies contributed a great quantity of research, development, data and knowlege to be applied to the construction of ships working in ice.

At the same time there was work on the design of fixed structures built of steel to withstand ice pressure.

The Canadian Government, to protect the environment, introduced in 1972 the Arctic Waters Pollution Prevention Act. The Arctic Shipping Pollution Prevention Regulations (ASPPR) accompanying this Act among, other requirements, laid down methods of calculation and ice loading forces for various classes of ice-going ships. With the introduction of the ASPPR the method of determining shell plating thickness and other scantlings was standardized to a degree never known before. Research still continues on loadings but consensus is achieved with the acceptance of these rules. The ASPPR has proved adequate in service but has only been tested over the lower range. As is the case with all good regulations it will be subject to revision as knowledge or experience requires.

The essence of the Canadian ASPPR (CASPPR) is that it specifies ten Arctic Classes for ships, divides the Canadian Arctic into geographic regions and then stipulates at what time of year a certain class of vessel can enter a certain region. (Figure 6.1). The classes

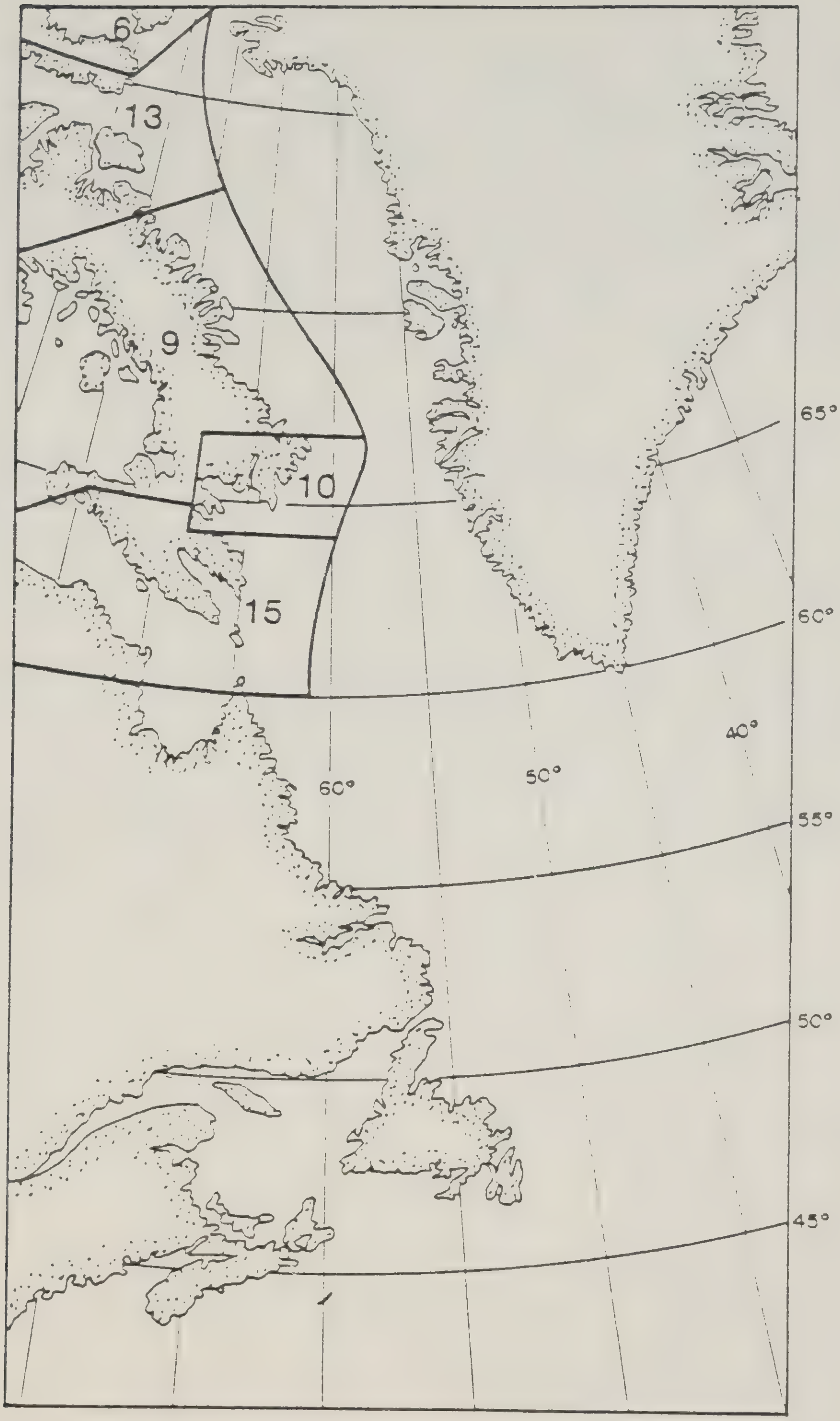

FIGURE 6.1 CASPPR Shipping Zones

range from 1 to 10 with 10 being the highest and permitting that vessel to go anywhere, anytime (Table 6.1). Recognition is given to the Classification Society ice ratings as Class A, B, C and D but these are all below the lowest Arctic Class 1. (Table 6.2). Bearing in mind that Class A (Lloyds Ice 1*) is specifically for navigation in the St. Lawrence River and Gulf, and that Class 4 is a good sized, typical icebreaker, one has some concept to the scope of the Regulations.

Notwithstanding that research work continues on maximum expected linearly disturbed pressures and point load forces and the structural analyses to optimize design response, there is sufficient knowledge and data to construct a class 10 vessel with confidence in the result.

It remains to be reaffirmed what class of vessel, or structure, is suitable to the areas of the East Coast operations. An attempt at this is currently being made in the formation of regulations for fishing vessels. The same should be done for supply boats and floating drilling platforms.

Column I Category	Column VII Zone 6	Column X Zone 9	Column XI Zone 10	Column XIV Zone 13	Column XVI Zone 15
Arctic Class 10 1.	All Year	All Year	All Year	All Year	All Year
Arctic Class 8 2.	All Year	All Year	All Year	All Year	All Year
Arctic Class 7 3.	All Year	All Year	All Year	All Year	All Year
Arctic Class 6 4.	Jul 15 to Feb 28	All Year	All Year	All Year	All Year
Arctic Class 4 5.	Jul 20 to Dec 31	Jul 10 to Mar 31	Jul 10 to Feb 28	June 1 to Feb 15	June 15 to Mar 15
Arctic Class 3 6.	Aug 1 to Nov 20	Jul 20 to Jan 20	Jul 15 to Jan 25	Jul 10 to Dec 31	June 20 to Jan 31
Arctic Class 2 7.	Aug 15 to Nov 20	Aug 1 to Dec 20	Jul 25 to Dec 20	June 25 to Nov 15	June 25 to Dec 20
Arctic Class 1A 8.	Aug 25 to Oct 31	Aug 10 to Dec 10	Aug 1 to Dec 10	Jul 15 to Oct 31	Jul 1 to Dec 10
Arctic Class 1 9.	Aug 25 to Sept 30	Aug 10 to Oct 31	Aug 1 to Oct 31	Jul 15 to Oct 15	Jul 1 to Nov 30
Type A 10.	Aug 15 to Oct 15	Aug 1 to Nov 20	Jul 25 to Nov 20	June 25 to Oct 22	June 25 to Dec 5
Type B 11.	Aug 25 to Sept 30	Aug 10 to Oct 31	Aug 1 to Oct 31	Jul 15 to Oct 15	Jul 1 to Nov 30
Type C 12	Aug 25 to Sept 25	Aug 10 to Oct 25	Aug 1 to Oct 25	Jul 15 to Oct 10	Jul 1 to Nov 25
Type D 13.	No Entry	Aug 15 to Oct 20	Aug 5 to Oct 20	Jul 30 to Sep 30	Jul 5 to Nov 10
Type E 14.	No Entry	Aug 20 to Oct 15	Aug 10 to Oct 20	Aug 15 to Sep 20	Jul 20 to Nov 5

SCHEDULE H

TABLE 6.1 Opening and closing dates for East Coast CASPPR zones for different ice class vessels (Arctic Waters Pollution Prevention Act, 1972)

Column I	Column II		Column III		Column IV	Column V	Column VI	Column VII	Column VIII
	Lloyd's Register of Shipping		American Bureau of Shipping		Bureau Veritas	Det Norske Veritas	Germanischer Lloyd	Registro Italiano Nevale	Nippon Kaiji Kyokai
Item	Baltic Service	General Service	1971 Rules	Baltic Service					
1. Type A	100 A1 Ice Class IA Super	100 A1 Ice Class 1*	-------	A1 Ice Class 1AA	I 3/3E Ice I Super	Class 1A1 Ice A*	100A4E 4	100A1.1 RG1	NS* Class AA
2. Type B	100 A1 Ice Class	100 A1 Ice Class 1	A1 Ice Class A	A1 Ice Class 1A	I 3/3E Ice I	Class 1A1 Ice A	100A4E 3	100A1.1 RG2	NS* Class A
3. Type C	100 A1 Ice Class 1B	100 A1 Ice Class 2	A1 Ice Class B	A1 Ice Class 1B	I 3/3E Ice II	Class 1A1 Ice B	100A4E 2	100A1.1 RG3	NS* Class B
4. Type D	100 A1 Ice Class IC	100 A1 Ice Class 3	A1 Ice Class C	A1 Ice Class 1C	I 3.3E Ice III	Class 1A1 Ice C	100A4E 1 or 100A4E	100A1.1 RG4	NS* Class C
5. Type E	100 A1	100 A1	A1	A1	I 3/3E	Class 1A1	100A4	100A1.1	NS*

SCHEDULE E

TABLE 6.2

(Arctic Waters Pollution Prevention Act, 1972)

6.2 Design Considerations

The ice parameters which need to be addressed in the design of an offshore unit are:

- The mass and impact speed of sea ice, growlers and icebergs, which directly affects the forces developed on the hull and structure of an offshore unit;
- The rate and total accumulation of ice (and snow accumulation, if applicable) on an offshore structure caused by climatic conditions. This additional environmental loading will affect both the structural design and the stability of an offshore unit; and
- The air and sea temperatures prevalent where ice is encountered may influence the selection of construction materials (e.g., high tensile steel) and the degree of 'weather proofing' required for safe, comfortable working conditions for offshore personnel.

Two sets of Canadian standards are relevant: The Interim Standards for the design, construction and operation of new Canadian registered mobile offshore drilling units (MODU's) recently distributed for comment by the Canadian Coast Guard (1983); and the Canadian Arctic Shipping Pollution Prevention Regulations (Arctic Pollution Prevention Act, 1972) for design, construction and operation of ships operating in Arctic waters (these are currently being revised).

The Interim Standards are based on the Intergovernment Maritime Oganization code (IMO, 1980) for the construction and equipment of MODU's with additional requirements specified by the Canadian Coast Guard on the basis of operational experience in Canadian waters. Part II of the Interim Standards, "Construction, Strength and Materials" (Canadian Coast Guard, 1983), contains the following statements regarding design loads:

13(1) The modes of operation for each unit shall be investigated using realistic loading conditions with relevant envirionmental loadings; the following environmental considerations shall be included, where applicable:

(a) wind forces, sustained and gust wind velocities as relevant shall be considered when determining wind loadings; pressures and resultant forces shall be calculated by the method referred to in Section 23 or by an equivalent method;

(b) (i) wave forces, the design wave criteria shall be described by design wave energy spectra or determinate design waves having appropriate shape and size; consideration shall be given to waves of lesser height, where due to their period, the effects on structural elements may be greater; and

(ii) wave forces utilized in the design analysis shall include the effects of immersion, heeling and acceleration due to motion; theories used for the calculation of wave forces and the selection of coefficients shall be to the satisfaction of the Board;

(c) current loadings, consideration shall be given to the interaction of current and waves and where necessary, this superimposition shall be performed by adding the current velocity vectorially to the wave particle velocity with the resultant velocity being used in calculating the structural loadings due to current and waves;

(d) ice and snow forces;

(e) mooring forces;

(f) temperature;

(g) extraordinary conditions such as the occurrence of earthquakes, fouling, etc. and

(h) any other loadings considered relevant by the Board.

2. The above design environmental conditions shall be based upon significant data with a period of recurrence of at least 100 years for the most severe anticipated environment.

3. Results from relevant model tests may be used to substantiate or amplify calculations.

It is evident from 13.1 (a), (b) and (c) that there are accepted procedures for calculation of design loads for wind, waves and current. However, for 13.1 (d) "ice and snow forces" of relevance to this study, there is no indication as to how these should be computed. Data on floating ice and icing conditions are scarce in many areas of eastern Canada, as are wind, wave and current data. However, the greater understanding of wind, wave and current forces permits more accurate extrapolation from limited data bases to arrive at reasonable estimates of 100 year return events, compared with the equivalent estimates for ice loadings.

In Part III, "Intact and Damage Stability and Freeboard", Section 21.4 dealing with sample loading conditions, it is noted that "For operations in the northern or eastern waters of Canada the variable deck load in each condition shall be adjusted to allow for the effect of ice and snow accumulation on the unit's structure". Again, there is no indication of the accuracy required in such load calculations.

The Section dealing with the extent of damage to surface (26.1) and column stabilized (26.2) units to be considered in assessing damage stability refers to hull breaks in the order of 3 m long with penetration of 1.5 m, with the vertical dimensions generally greater than 3 m. The lower hulls or footings are assumed to be liable to damage only when operating in a light or transit condition (25.2(v)).

The Det norske Veritas (1982) rules for the classification of MODU's require the platform to be able to survive not less than 14 MJ of kinetic energy for a sideways impact with a supply vessel, and 11 MJ for a bow or stern collision. The supply vessel is assumed to be 5,000 tonnes displacement, with an impact speed of 2 ms^{-1}. The impact speed caused by wave induced motion of the supply vessel is assumed to be $0.5H_s$ ms^{-1}, where H_s is the maximum significant wave height in metres. The vertical extent of the collision zone is based on the depth and draught of the visiting supply vessel, and the relative motion between the vessel and the MODU.

With respect to floating ice on the east coast of Canada, most of the concern has centred on large icebergs in the 10^5 - 10^7 tonnes range, moving at maximum speeds of between 1 and 2 ms^{-1}. However, these large icebergs are relatively easy to detect in sufficient time to take any action necessary to ensure the safety of the vessel or drilling operations. The major ice hazard is actually presented by bergy bits and growlers that are extremely difficult to detect, particularly under adverse weather conditions.

As iceberg mass is reduced, the influence of ocean waves on the dynamics of the ice increases. Since substantial energy exists in storm waves, much higher instantaneous velocities may result for relatively smaller ice masses in these waves than their mean hourly drift values. Investigation into the kinematics and dynamics of small icebergs and bergy bits in waves has only recently been undertaken. According to Hsiung and Aboul-Azm (1981), an iceberg as large as 200,000 tonnes in 1.5m amplitude, 12s waves, may experience a second-order wave force in excess of the sum of all other environmental forces.

Very little quantitative data presently exists on expected instantaneous velocities of icebergs in waves, and no field data exists at all. Lever et al. (1984) recently conducted wave tank tests to determine the kinematics of small ice masses in storm waves typical of the Grand Banks region (10-14s periods, 12-15m heights). The results of these tests may be summarized as follows:

- Ice masses small compared to a wavelength moved essentially as particles of fluid in finite amplitude waves. Maximum full scale velocities of 4.5 ms^{-1} could be achieved in 14m, 12s waves for a bergy bit of mass 4,300 tonnes. The resulting kinetic energy of 40 MJ is three times larger than the kinetic energy assumed by DnV (Det norske Veritas, 1982) for a sideways collision between supply vessel and a MODU.
- A model ice-structure impact was documented which would correspond in full scale to a 4.5 ms^{-1} collision between a 1,500 tonne bergy bit (kinetic energy about 10 MJ) and a 8.6 m diameter column. Ice-structure impacts were not observed in

all cases, indicating that the structure may modify the local behaviour of the ice under certain conditions.

The hazard posed by the wave-induced motion of small ice masses is further increased by consideration of: the shorter impact durations resulting from higher impact velocities; the inability to detect such small masses; the difficulty in implementing iceberg management techniques in heavy seas; the potential for localized impacts with smaller structural members; the possibility of the ice being trapped within an open structure for repeated impacts.

While the results of Lever et al. (1984) indicate the serious nature of the impact hazard posed by the wave-induced motion of small ice masses, much more field, laboratory and theoretical work is required in this area. However, it is possible the extent of "permissible" damage assumed in the regulations may not be realistic in the case of ice impact. Also, the draft of an undetected bergy bit may be sufficient to damage the lower hull of a column stabilized unit even at drilling or survival draft.

In addition to the Canadian standards, the rules and regulations of the following agencies have been considered:

- United Kingdom Department of Energy (1981)
- Norwegian Maritime Directorate (1976)
- Newfoundland and Labrador Petroleum Directorate (NLPD) (1982c)
- American Bureau of Shipping (ABS) (1978, 1980)
- American Petroleum Institute (1982a, 1982b)
- Lloyd's Register of Shipping (1982)
- Det norske Veritas (DnV) (1982)
- Bureau Veritas (1975)
- Germanischer Lloyd (1976)
- International Maritime Organization (IMO, 1980).

The subject of designing an offshore structure/unit for use in waters where sea ice or icebergs are prevalent is also addressed by the regulatory bodies in varying degrees dependent on both their relevant jurisdiction and experience. For instance, the Newfoundland

regulations (Newfoundland and Labrador Petroleum Directorate, 1982c) for the design of offshore installations state that all relevant sea ice and iceberg conditions are to be considered and, for a floating unit, the mooring system shall be capable of quick-release in the event of a severe ice threat. ABS also refers to the total (sea) ice forces developed on a structure and offers a formulation for deducing the total force based on experience derived in the Canadian/American Beaufort Sea and Cook Inlet (Alaska). Such ice specific requirements reflect the fact that for American and Canadian authorities sea ice is an important factor to be considered, whereas it is less so for others, such as United Kingdom Department of Energy whose area of jurisdiction is virtually free of sea ice and icebergs. Since the bulk of world wide offshore exploration and development activities to date have taken place in ice-free waters the question of sea ice and iceberg interaction with offshore structures and exploration units has not received the same attention as other environmental concerns (such as wind and wave loading).

Typically, the Classification Societies require that in the design calculations submitted for a MODU, the effects of icing on structural loadings and stability are to be considered. However, no general criteria (such as exists for wind loading) is specified for ice accretion on semi-submersibles or jack-ups. This reflects the current lack of experience available for offshore operations in ice-prone areas. However with market demands for 'hostile' environment rig designs, ice loadings must be included in the variable deck loading in the design development. Therefore the designer is responsible for developing representative ice loads based on rational icing scenarios. Drill ships have icing loads calculated on the basis of the requirements of the IMO for normal commercial vessels operating in areas where icing occurs.

Work has been carried out by Norwegian and Canadian researchers in developing theoretical methods to calculate the icing amounts likely to accumulate on semi-submersibles based on the rig configuration and climatic conditions specific to a given site. Such studies will

provide the basis for standardizing the treatment of icing aboard offshore units.

Techniques for preventing ice accretion (such as low friction paints) or for assisting its removal by novel means (including heating elements and inflatable pneumatic panels) are also being investigated but no one method or system has emerged as being suitable for implementaion on a practical basis. Current design philosophy for offshore units expected to be subjected to icing is to maximize the use of flush surfaces whenever possible (especially on platforom undersides) and to enclose ice-prone equipment (mooring winches, derricks, etc.).

In summary, icebergs, sea ice and icing in terms of offshore design have not been a significant factor to date but with the increasing activity in hostile areas (such as offshore Eastern Canada and in the Northern North Sea) these concerns are receiving closer attention from both the regulatory agencies and the private sector. It would appear that further research is required in order to develop methods to accurately assess the degree of ice accretion likely to occur under given climatic conditions. The effects of floating ice impacts on the structure of offshore units is also an area warranting further investigation.

6.3 Operational Conditions

None of the drilling vessels in general use off eastern Canada, namely, drill ships, semi-submersibles, or jack-ups, are specially adapted to resist the effects of direct interaction with floatng ice or to minimise the effects of superstructure icing. Certain semi-submersibles have been designated as "ice-strengthened", for example the SEDCO 706, although it is not clear what this designation means, other than that some additional stiffening has been incorporated in columns which could be subjected to ice impact. However, a number of supply vessels are ice strengthened in accordance with one or more of the Certification Societies criteria - for instance, Lloyd's Arctic 2 or 3. Throughout the region, the key to safe operations in the presence of potentially hazardous floating ice in the form of sea ice or glacial ice, is early detection, followed by successful avoidance or deflection of the ice if it is expected to come within a predetermined distance of the drilling location.

The Interim Standard for MODU operations (Part XIV) (Canadian Coast Guard, 1983) require "ice alert" procedures be described in the operations manual, compliance with the Navigating Appliance Regulations of the Canada Shipping Act (1970), and with the Arctic Shipping Pollution Prevention Regulations for operations north of 60^{o}N latitude. The physical environment guidelines for drilling programs in the Canadian offshore issued by COGLA contain detailed instructions for iceberg, sea ice and icing data collection, forecasting, and for preparation of monthly summaries of the various environmental parameters. The objective of the regulations is, in all cases, to minimise the possibility of impact between floating ice and the MODU or supply boat.

The "ice alert" procedures for floating ice have been described in detail in section 2.4. In principle, icebergs must be detected as soon as possible - COGLA requires 50 km. However, experience has shown this is often not possible even with the larger icebergs, and impossible for bergy bits and growlers. The icebergs are to be monitored at hourly intervals and plotted with an accuracy of 0.4 km

and resolution of 0.2 km. For dynamically-positioned drillships the disconnect zone has a radius of 1 km. The next zone extends from 1 km to either a distance equal to twice the hourly drift speed of the iceberg, or the number of hours required to secure the well times the drift speed - whichever is greater being used to define the outer limit of the zone. The next zone extends from this distance to four times the hourly drift speed, or the number of hours needed to secure the well times the drift. Again, whichever is greater being used. Beyond this distance, icebergs are simply tracked with forecasts of their future drift being developed hourly.

For anchored drilling systems, the operational routine calls for ice to be detected as soon as it comes within 200 km of the drilling location. When it comes within 80 km of the site, a supply boat is usually sent to tow or stand by the iceberg until it is outside the 80 km zone again. Disconnect procedure, both drilling and anchors, are initiated when the iceberg comes within 40 km. Not all anchors are let go immediately. For instance, when an iceberg came within 10 km of a rig operating on the Grand Banks during January, 1983, the rig had let go all but two anchors before the ice drifted away again.

These procedures have evolved from operational experience, and with time have become accepted by the regulatory authorities. The one potential weakness of the "ice alert" procedures is the possibility of icebergs, particularly bergy bits and growlers, escaping detection and colliding with a drilling vessel. General hazard detection standards are layed down in the Navigating Appliance Regulations of the Canadian Shipping Act. Schedule D of these regulations requires that a ship's radar be capable of clearly displaying under normal propagating conditions, an object having a reflecting area of 10 m^2 at ranges between approximately 100 m and 4,000 m. In terms of glacial ice, such a target might correspond to a growler 10 m^3 with a freeboard of approximately 1 m, weighing approximately 1,000 tonnes. Such a small piece of ice is likely to be moving with the waves and, having rolled many times, to be well rounded. Experience, particularly aboard the drill ships off Labrador with an ice observer on duty at all times, indicates such a target would be almost impossible to detect with

conventional marine radars because of its lack of clear cut reflecting surface. Also, if the waves are significantly more than 1 m in height, the lack of continuous line of sight between the radar antenna and the ice further aggrevates the problem of detection. This situation does not improve close to the vessel, as the return from the ice can be lost in a sea clutter under such conditions.

The COGLA guidelines also outline specific requirements for site specific weather and sea state forecast services. These forecasts, which must be issued at least every 12 hours with six hour or more frequent updates, must include information on freezing spray and freezing precipitation. Although there are established procedures for predicting these conditions, there is very little information on which to assess the impact of such loads on the stability, and the extent to which accreted ice hampers crew movement about the supply boats and drilling vessels.

When drilling operations are conducted in the presence of pack ice or icebergs, local, tactical forecasts are required at least every three hours. In recognition of the inadequacies of the data bases for most environmental parameters for the Canadian Offshore regions, COGLA requires monthly histograms of ice thickness, floe sizes and speeds, ridge heights and keel depths, and iceberg dimensions and drift speeds. Relationships between drift speed and iceberg mass and iceberg draft are also to be provided. Finally, a forecast verification must be provided.

6.4 Emergency Situations

NORDCO has carried out a survey of regulatory requirements for lifesaving equipment aboard offshore vessels and has also examined the proceedings of a number of symposia on safety and emergency management in offshore operations, both for Canadian and international theatres.

A number of risk analyses have been carried out for drilling units operating offshore Newfoundland and Labrador. In these analyses the possibility of iceberg collision with a moored, dynamically-positioned or in-transit drilling unit was considered a significant risk and recommendations were made to reduce this risk factor. The influence of sea ice or ice accretion on emergency measures or rig evacuation is not directly addressed in these studies. However, sea ice can be expected to hamper standby/rescue vessels from rendering aid and ice accretion can cause difficulties in proper functioning of lifesaving equipment (e.g. the lifeboat davits).

The regulatory agencies do not directly specify the need for lifesaving equipment (lifeboats, rafts, davits, etc.) to be rated for operation in any particular ice regime or under freezing conditions (Part X of the Canadian Coast Guard (1983) Interim Standards for MODU's). A recent Norwegian study into new concepts of evacuation from offshore installations, though extensive in its scope, makes no mention of icing and its effect on the successful deployment of any of the equipment considered in the study. Since a study conducted for the U.S. Coast Guard indicated that in the abandonment of 51 large commercial vessels 60% of the total fatalities could be attributed to failure of the lifeboat/raft launching systems (with a definite relationship to prevailing weather conditions at the time), then the even greater difficulties in successfully launching emergency equipment from a semi-submersible/platform should include the effects of icing on equipment operation.

The recently commissioned Conical Drilling Unit (CDU), "Kulluk", a circular mobile drilling vessel intended for operations in ice frequented waters typical of the Beaufort Sea, carries novel

lifesaving equipment. This example of an evacuation system designed for ice frequented waters, appears to consist of an inflatable slide (similar to those for emergency exit from aircraft), that terminates at water level with a boarding platform and two rafts. The "Marine Evacuation System" is installed 9.5 m above the operating water line, the slide is 20 m long and the boarding platform is 7.5 m across. The two liferafts each hold 42 men. The system has been successfully tested in sheltered waters with 20 crew men dressed in exposure suits, and has been approved by the Canadian Coast Guard for use aboard the CDU in the Beaufort Sea (North Sea Observer, 1983). Although designed for ice frequented waters, it remains to be seen how vulnerable the system might be to puncture by ice and how manageable it might be under typical east coast sea conditions.

A major component of any search and rescue activity off Canada's east coast is the aircraft. Unfortunately search and rescue situations often occur in bad weather and this may prevent the aircraft from flying or, even when a flight is possible, visibility restrictions may prevent them from undertaking effective search activities. Also, helicopters are not able to fly in areas where icing is occurring and fixed-wing aircraft can only fly in icing conditions for short periods if the conditions are severe. Therefore, the occurrence of icing conditions in the search and rescue area may also prevent flying at an altitude low enough to provide effective reconnaissance.

A recent study on search and rescue in Canada criticized the government for not undertaking sufficient research and development activity in the area of remote detection technology (Canada Cabinet Committee report on Foreign and Defence Policy, 1982). It is apparent that the prevailing poor visibility severely restricts the effectiveness of visual reconnaissance. Hence, there is a requirement for the evaluation of sensing devices similar to that being carried out for ice hazards.

6.5 Assessment

(i) Design and construction standards for vessels operating in ice infested waters have been developed by Classification Societies, largely for insurance purposes. The Arctic voyage of the "Manhattan" in 1969 was closely followed by promulgation of the Arctic Waters Pollution Prevention Act, and the accompanying Arctic Shipping Pollution Prevention Regulations. These regulations, for the first time, specified the design and construction standards required for vessels operating north of 60°N latitude within 100 miles of the Canadian coastline. These regulations apply to exploration activity north of 60°N latitude - including the dates of entry and exit from these waters for different ice class vessels. The design regulations do not specifically refer to MODU's.

(ii) The Interim Standards for the design, construction and operation of MODU's recently issued by the Canadian Coast Guard, generally require ice loadings to be calculated for 100 year return events. However, as is evident from previous chapters of this study, there is not sufficient information on most ice parameters to calculate realistic 100 year events.

(iii) All exploratory drilling vessels operating in the vicinity of floating ice have sophisticated ice management systems, with clearly defined operating procedures should approaching ice pose a hazard to the operations. However, these management systems rely on detection of hazardous ice and it is doubtful whether present technology is adequate for detection of small bergy bits and growlers under adverse weather conditions.

(iv) A number of theoretical studies have been carried out in order to estimate the damage a small, undetected piece of ice is likely to inflict on a MODU. Recent laboratory experiments indicate the energies involved may be significantly greater than those assumed by Classification Societies for supply boat collision with a MODU. However, the collision forces are dependent on the behaviour of

the ice on impact and there have been no large scale experiments to verify the theoretical assumptions. Such experiments are needed to determine damaged stability requirements for MODU's, as well as strengthening requirements when contact with floating ice is likely to be a common occurrence.

(v) Several European countries have MODU designs for severe weather operations. The advantages of such vessels are flush surfaces to minimize structural icing and covered work and emergency assembly areas. Several of these designs have "ice strengthening", but it is not clear how effective such reinforcing would be in the event of a collision with glacial ice.

(vi)Very little consideration appear to have been given to the operation of exposed emerency equipment, such as lifeboats and liferafts, under freezing spray or precipitation conditions. Also, it is not clear from regulations whether lifeboats or liferafts could operate in loose pack ice without a significant risk of hull puncture.

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